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EVALUATION OF WES ANALYTICAL MODEL IN SELECTED TERRAINS (XM559E1 GOER TESTS AT CAMP GAGETOWN, NEW BRUNSWICK, CANADA)

ARMY ENGINEER WATERWAYS EXPERIMENT STATION,
VICKSBURG, MISSISSIPPI

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13. ABSTRACT

This study was conducted to (a) evaluate the performance of the 8-ton XM559E1 GOER when operating in selected Canadian terrains and (b) evaluate the capability of the WES analytical model to predict the performance of an 8-ton XM559E1 in selected Canadian terrains. Speed and motion resistance tests on secondary roads, cross-country speed tests, drawbar pull-slip tests, and towed off-road motion resistance tests were conducted. Where pertinent, soil, surface geometry, and vegetation data were collected before or after each test, and speed, vertical and longitudinal accelerations, percent wheel slip, and drawbar pull were measured. A comparison was made of actual performance and performance as predicted by the analytical model. The average of the absolute deviation of actual from predicted speeds for the tests conducted was 1.36 mph.

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EVALUATION OF WES ANALYTICAL MODEL IN SELECTED TERRAINS (XM559E1 GOER TESTS AT CAMP GAGETOWN NEW BRUNSWICK, CANADA)

by

B. G. Stinson

DRAFT

March 1970

Sponsored by U. S. Army Tank-Automotive Command

Conducted by U. S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

ARMY-MRC VICKSBURG, MISS.

FOREWORD

The study reported herein was performed by the U. S. Army Engineer Waterways Experiment Station (WES) in cooperation with the Defence Research Board (DRB), Ottawa, Ontario, Canada, for the U. S. Army Tank-Automotive Command (TACOM). The field tests were conducted in July 1968 at Canadian Force Base (CFB), Gagetown.

The study was conducted by personnel of the Vehicle Studies Branch (VSB), Mobility and Environmental (M&E) Division, under the general supervision of Mr. W. J. Turnbull, Technical Assistant for Soils and Environmental Engineering; Mr. W. G. Shockley, Chief of the M&E Division; Mr. S. J. Knight, Assistant Chief of the M&E Division; Mr. A. A. Rula, Chief, Vehicle Studies Branch; and Mr. J. K. Stoll, Chief, Obstacle-Vehicle Studies (OVS) Section. Design and execution of the testing were under the direct supervision of Mr. B. G. Stinson, OVS Section. Mr. C. A. Blackmon, OVS Section, conducted the field test program and maintained liason between WES and DRB and CFB Gagetown. This report was prepared by Mr. Stinson.

Director of the WES during the test program and preparation of this report was COL Levi A. Brown, CE. Technical Director was Mr. J. B. Tiffany.

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CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	2.54	centimeters
feet	0.3048	meters
miles	1.609344	kilometers
gallons (U. S.)	3.785412	cubic decimeters
pounds	0.45359237 4.448	kilograms newtons (N)
short tons (2000 lb)	907.185	kilograms
pounds per square inch	4.88243	kilograms per square meter
foot-pounds	0.138255	meter-kilograms
feet per second	30.48	centimeters per second
miles per hour	1.609344	kilometers per hour
horsepower	745.700	watts

SUMMARY

This study was conducted to (a) evaluate the performance of the XM559E1 GOER when operating in selected Canadian terrains and (b) evaluate the capability of the WES analytical model to predict the performance of an 8-ton XM559E1 in those terrains.

Speed and motion resistance tests on secondary roads, cross-country speed tests, drawbar pull-slip tests, and towed off-road motion resistance tests were conducted. Where pertinent, soil, surface geometry, and vegetation data were collected before or after each test, and speed, vertical and longitudinal accelerations, percent wheel slip, and drawbar pull were measured. A comparison was made of actual performance and performance as predicted by the analytical model.

The average of the absolute deviation of actual from predicted speeds for the tests conducted was 1.36 mph.

EVALUATION OF WES ANALYTICAL MODEL IN SELECTED TERRAINS (XM559E1 GOER TESTS AT CAMP GAGETOWN, NEW BRUNSWICK, CANADA)

PART I: INTRODUCTION

Background

1. As a part of an effort on terrain classification begun under the auspices of the now defunct Quadripartite Standing Working Group on Ground Mobility, the U. S. Army Engineer Waterways Experiment Station (WES) participated in the Canadian Camp Petawawa Exercise held in July 1967. This exercise was the first of two planned by the Defence Research Board (DRB), Ottawa, Ontario, Canada. During the exercise, three vehicles (an M113A1, an M37, and an M38) were run on cross-country traverses selected in a variety of terrain types.

2. In March 1968 DRB invited WES to participate in a second exercise to be held at Canadian Force Base (CFB), Gagetown, New Brunswick, Canada, on 8-19 July 1968. The DRB program included cross-country tests of two vehicles, an M113A1 armored personnel carrier and a Centurion tank. WES accepted the invitation.

3. In the meantime the WES was contacted by the U. S. Army Tank-Automotive Command (TACOM) Project Manager, GOER, who requested that WES participate in a field test program designed to validate and/or evaluate the WES analytical model for predicting cross-country vehicle performance, using an 8-ton* XM559E1 GOER as the test vehicle. It was mutually agreed by WES and TACOM that the task of evaluating the WES analytical model with the GOER could be accomplished

* A table of factors for converting British units of measurements to metric units is presented on page vii.

during the 8-19 July test program at CFB Gagetown; therefore, WES obtained permission from DRB to include an 8-ton GOER in the field testing.

Purpose

4. The purpose of the tests reported herein was to (a) evaluate the performance of the XM559E1 GOER when operating in selected Canadian terrains and (b) evaluate the capability of the WES analytical model to predict the performance of an 8-ton XM559E1 in those terrains.

Scope

5. Terrain and vehicle performance data were obtained from nineteen tests of five types conducted on 8 test courses using an 8-ton XM559E1 GOER:

No. of Tests Conducted	Type of Test
2	Speed on secondary roads
11	Cross-country speed
4	Drawbar pull-slip
1	Towed off-road motion resistance
1	Motion resistance on secondary roads

Where pertinent, soil, surface geometry, and vegetation data were collected for each test, and speed, vertical and longitudinal accelerations, percent wheel slip, and drawbar pull were measured. Comparisons were made of actual performance and performance as predicted by the analytical model.

Definitions

6. Special terms used herein are defined below.

Cone index (CI). An index of soil consistency or strength. It is the force per unit area required to move a 30-deg, right circular cone of 0.5-sq-in. base area through the soil at a rate of 72 in. per min. This force per unit area is expressed in pounds per square inch of base area of the cone.

Remolding index (RI). A ratio that expresses the proportion of the original strength of a medium that will be retained after traffic by a moving vehicle. The ratio is determined from cone index measurements made before and after remolding a 6-in.-long sample.

Rating cone index (RCI). The product of the remolding index and the average of the measured in situ cone index for the same layer of soil. This index is valid only for fine-grained soils and for sand with fines, poorly drained.

Slip. The percentage of track or wheel movement ineffective in thrusting the vehicle forward.

Rolling circumference. Forward advance per revolution of the loaded tire when towed on a plane, level, unyielding surface. It is related to the tire diameter and the deflection. Rolling radius is obtained by dividing rolling circumference by 2π.

Deflection. Difference, in percent, between the section height and the loaded section height of the tire.

Load. The vertical force applied to the tire through the axle including the weight of the wheel and tire.

Muskeg (organic soil). The living, dying, and dead vegetation that forms a surface mat, and the mixture of partially decomposed and disintegrated organic material (commonly known as peat or muck) below the surface mat. Small quantities of mineral soil may or may not be mixed with the organic material.

PART II: TEST PROGRAM

Location and Description of Test Areas

7. All test areas were within the boundaries of the CFB Gagetown. The north boundary of CFB Gagetown is about 10 miles southeast of Fredericton, New Brunswick, and the south boundary is about 20 miles northwest of St. John (see fig. 1).

8. The maximum relief over most of the base is approximately 200 ft, and the topography is gently rolling. Local drainage conditions vary greatly throughout the area, depending largely on topographic features. The land, in slight depressions and on gently undulating topography, is often poorly drained, and the water table of the soil often rises close to the surface. The entire area has been subjected to glaciation, and practically all the upland soils have formed from weathered glacial till. The surface soils are usually quite friable and contain numerous rock fragments and occasional boulders. The soil immediately below the surface layer is generally reddish brown. In the subsoil, at depths of 2 to 3 ft, the unweathered till consists chiefly of reddish brown compact boulder clay and silty clay. The cover of till over the bedrock is usually 3 to 5 ft thick, but frequently the depth of the till is less than 3 ft and occasionally bare outcrops of rock are found.

9. Except for relatively small, cleared areas near the center of the base, the land is covered with mixed forest vegetation. There is a

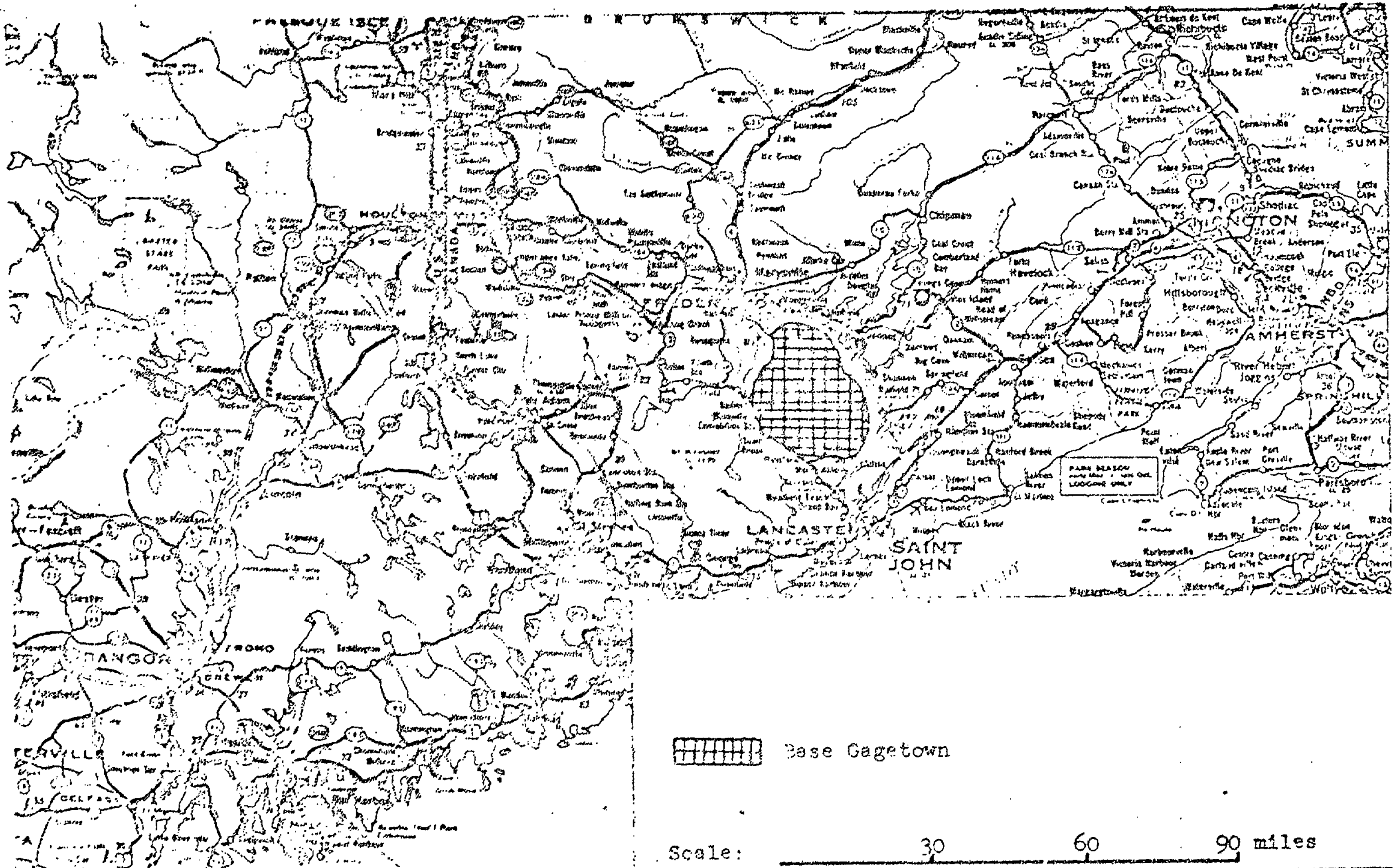


Fig. 1. Vicinity map, Canadian Force Base Gagetown

natural tendency for trees to displace grasses as evidenced by many former pastures in which the trees are encroaching and displacing the pasture vegetation. Approximately 16 species of trees, including both deciduous and conifers, commonly occur in the area in a wide variety of sizes and distributions. Much of the variation in structural assemblages is due to methods of cutting in lumber operations and to forest fires.

Test course 1

10. Test course 1 was located on CFB Gagetown about 21 miles south 37 deg east of the headquarters complex (see fig. 2). The course was a secondary road surfaced with a mixture of crushed stone and soil. The length of the test course is 2700 ft. On the day the tests were conducted the surface was dry and firm, but there was a small amount of loose gravel on the surface. The magnitudes of surface irregularities were not great enough to affect vehicle performance significantly. The slope of the course ranged from 3 to 12 percent; the average for the entire course was 6.64 percent. Test course 1 is shown in fig. 3.

Test course 2

11. Test course 2 was about 19 miles south, 29 deg east of the headquarters complex of the CFB Gagetown (see fig. 2) in an area that is primarily used for general maneuver purposes. The test course is 2500 ft long. The surface soil was silty sand, classified as SM by the USCS. The surface was dry at the time of the tests; the average cone indexes of the 0- to 6-in. and 6- to 12-in. layers were 120 and 205, respectively. The surface irregularities were caused either by natural erosion or by military vehicles during maneuvers in the wet season.

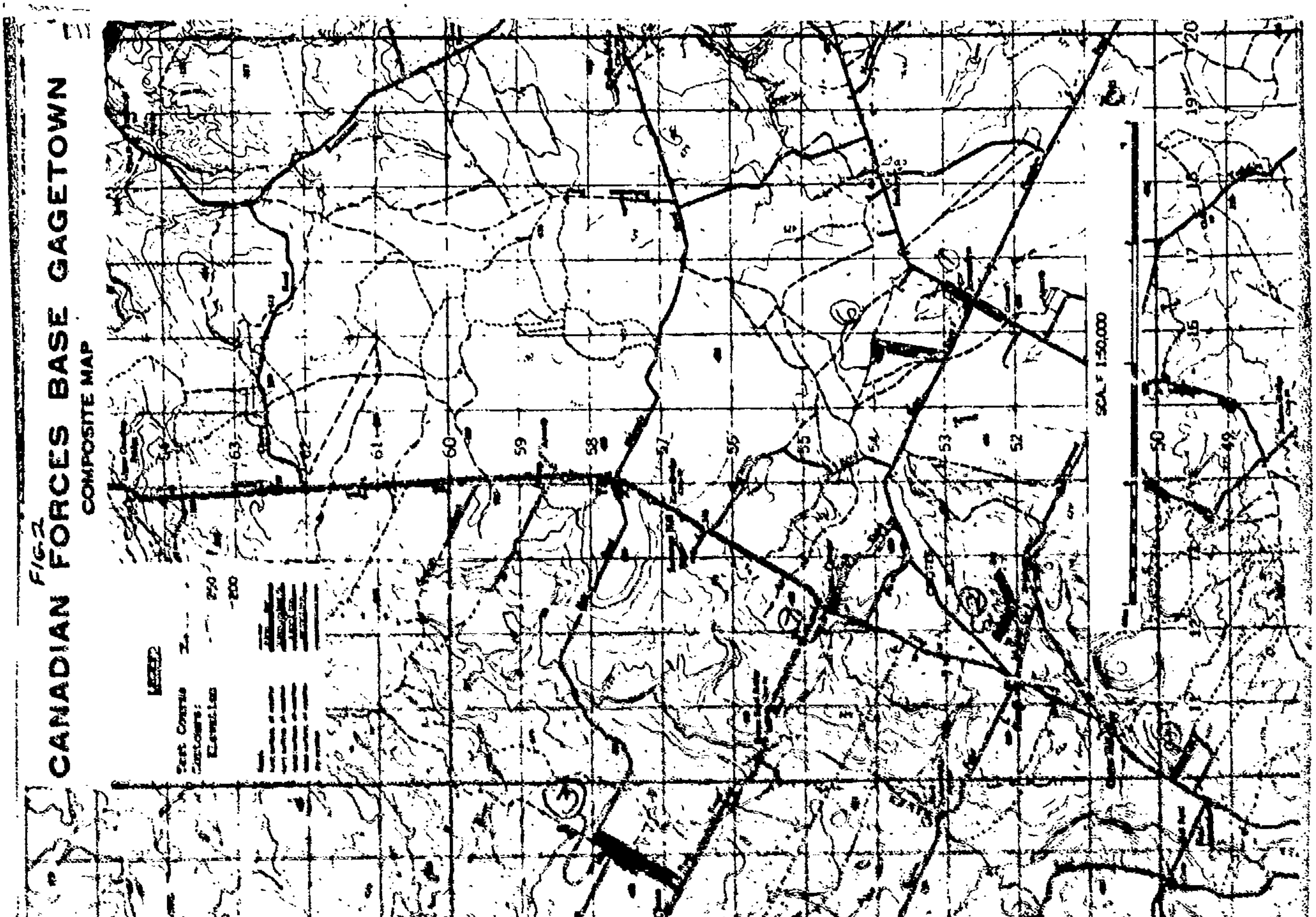


Fig. 2. Canadian Forces Base Gagetown

Fig. 3. Test course 1

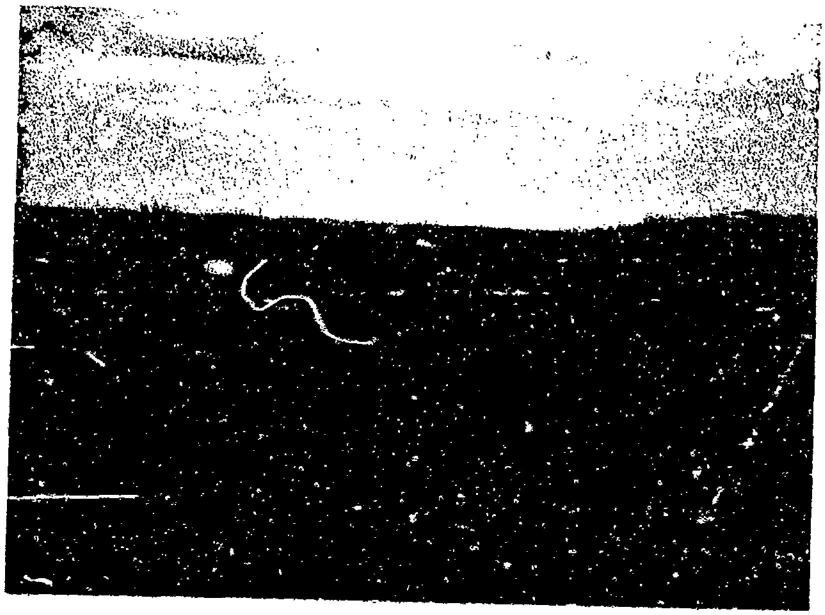
The slope of the course ranged from 3 to 19 percent and averaged 10.2 percent. There was a small stream near the center of the test course but at the time of test the water depth was less than 6 in. The bottom of the creek was composed of sand and rocks, and the slope of the banks was less than 10 deg; therefore, the stream did not present a serious mobility problem. The vegetation over the test course was short grass except for a 20-ft-wide strip along the stream where there was a stand of 1- to 3-in.-diam hardwood trees spaced about 1 ft apart. Test course 2 is shown in fig. 4.

Test course 3

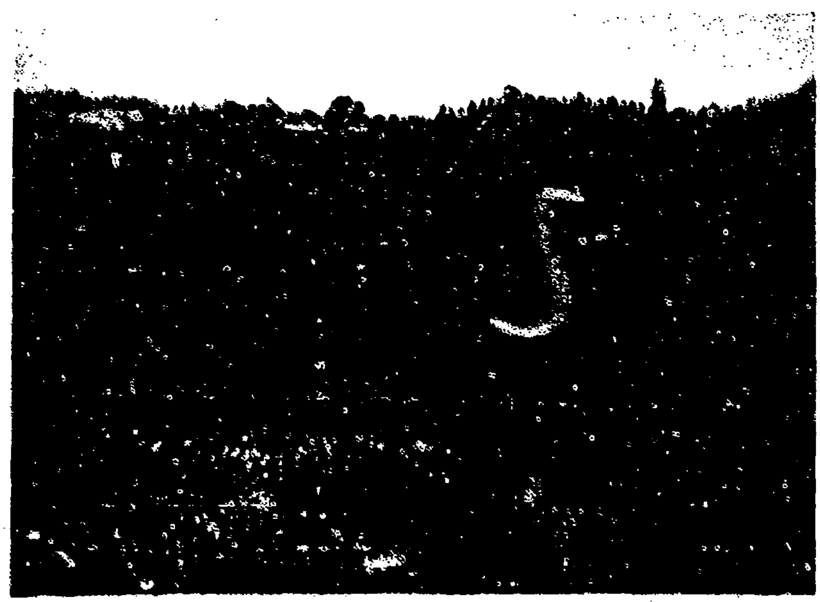
12. This test course was located 16.1 miles south, 27 deg east of the CFB Gagetown headquarters complex (see fig. 2). The length of this test course is about 0.9 miles. The course was in a densely forested area. Tree stems ranged from 1 to 7 in. in diameter; the smaller trees were about 5 ft apart and the larger trees about 18 ft apart. The surface was flat (zero slope) with no significant irregularities. The surface foot of soil was silty sand with some organic material (SM). The depth to bedrock was about 3 ft. At the time the tests were conducted, the average cone indexes of the 0- to 6-in. and the 6- to 12-in. layers of soil were 120 and 347, respectively. Test course 3 is shown in fig. 5.

Test course 4

13. Test course 4 was located 11 miles south, 23 deg east of the CFB Gagetown headquarters complex (see fig. 2). The total length of the test course is about 1 mile. The top 20-32 in. of the surface was composed of muskeg. Beneath the muskeg was a sandy mineral soil

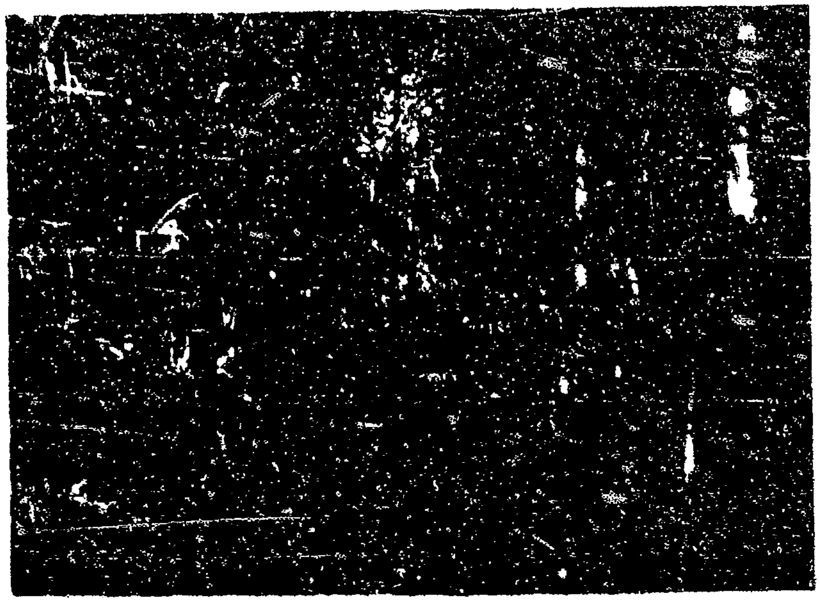


a. General view

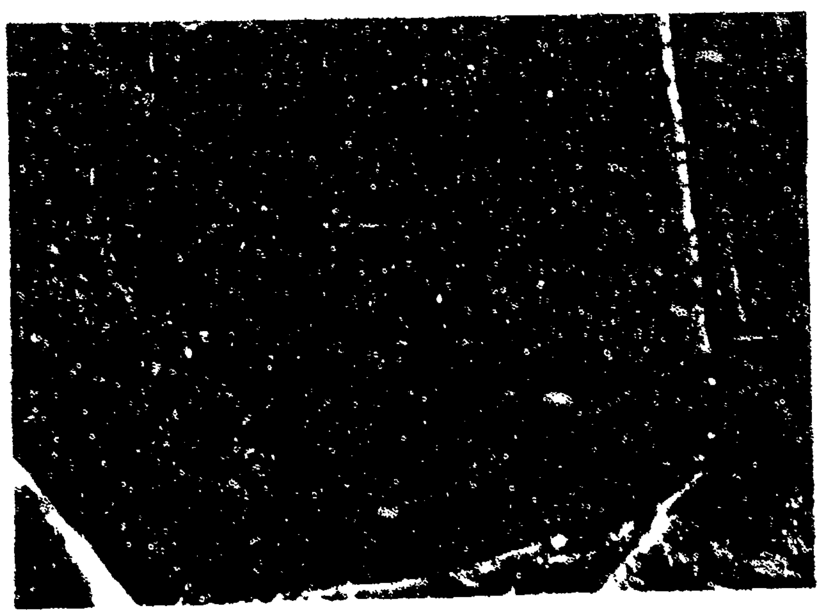


b. Small stream crossing near center of test course

Fig. 4. Test course 2



a. General view



b. Point of XM559 GOER immobilization

Fig. 5. Test course 3

classified as SM by the USCS. The Radforth* classification system for muskeg classed the vegetal coverage as EFI and the organic material (peat) as woody, fine-fibrous held in a woody, coarse-fibrous framework (type 9). The average cone indexes of the 0- to 6-in. and 6- to 12-in. layers of muskeg at the time the tests were conducted were 21 and 38, respectively. The magnitude of surface geometry features was not great enough to significantly affect mobility. Vegetation was predominantly grass about 12 in. high. Test course 4 is shown in fig. 6.

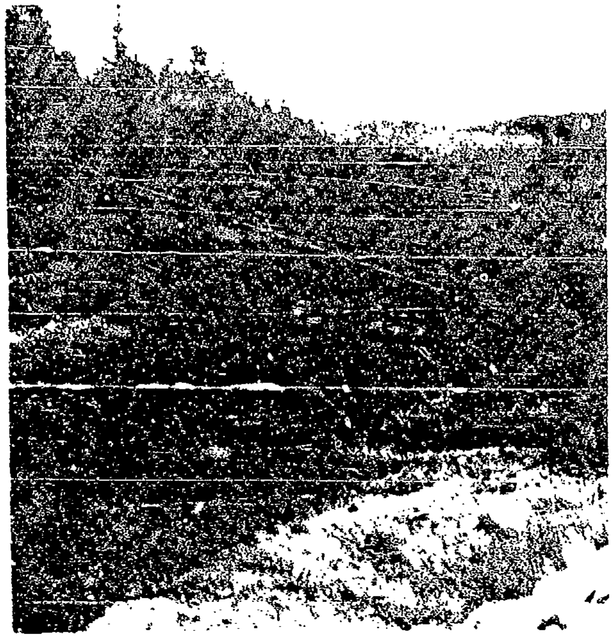
Test course 5

14. This course was 11 miles south, 25 deg east of the CFB Gagetown headquarters complex (see fig. 2) on an upland flat. The test course is 1000ft long. The topographic slope averaged about 2 percent. The surface was irregular due to outcropping rocks. The most serious surface irregularities had approach angles ranging from 30 to 45 deg, step heights from 16 to 20 in., and were randomly spaced. The surface was composed of about 1 in. of forest litter and sandy (SM) soil over bedrock. Cone indexes could not be measured because of the denseness of the bedrock; however, tree roots were growing in the cracks in the rocks. The trees were predominantly coniferous with stem diameters ranging from 1 to 4 in. and were spaced about 4 ft apart. Test course 5 is shown in fig. 7.

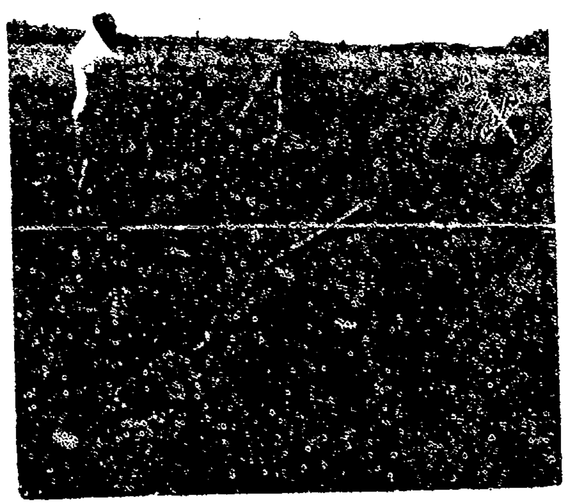
Test course 6

15. This course was 19.5 miles south, 35 deg east of the CFB Gagetown

* National Research Council, Canada; Associate Committee on Soil and Snow Mechanics, "Guide to a Field Description of Muskeg (Based on the Radforth Classification System)" compiled by I. C. MacFarlane, Technical Memorandum 44 (rev ed), June 1958, Ottawa.



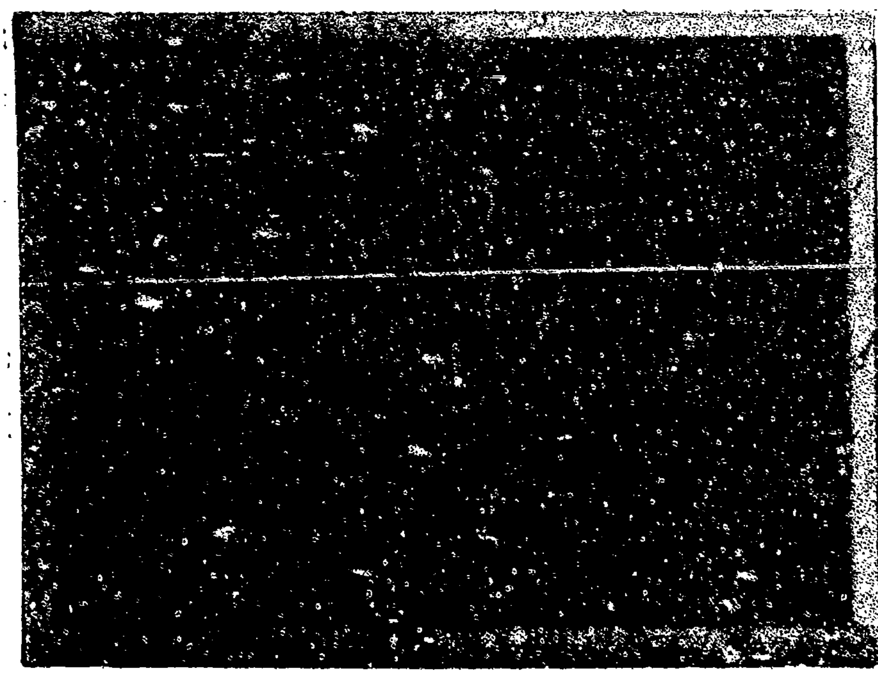
a. Point of XM559 GOER immobilization during test 7



b. Point of XM559 GOER immobilization during test 8

Fig. 6. Test course 4

a. General view



b. Test course after one pass of GOER

Fig. 7. Test course 5

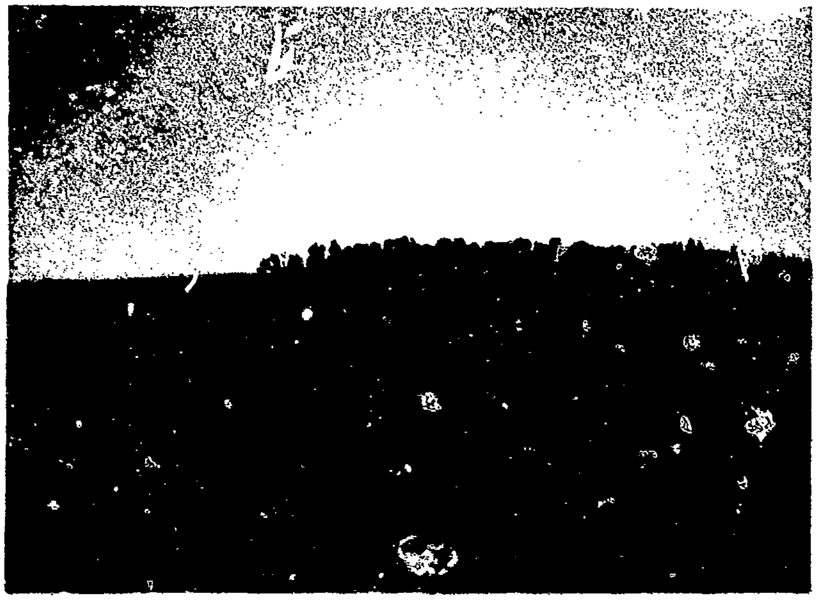
headquarters complex (see fig. 2) in an upland plateau that is normally used for general maneuver purposes; as a consequence, numerous tank tracks crisscrossed the test area. The test course is 3000 ft long. The average topographic slope was 2 percent. The surface irregularities were mostly tank ruts. The most critical surface irregularities had approach angles ranging from 30 to 45 deg and step heights from 8 to 10 in. and were randomly spaced. The soil to a depth of 12 in. was silty sand (SM). The average cone index of both the 0- to 6-in. and 6- to 12-in. layers was greater than 300. The vegetation throughout the test course was short grass. Test course 6 is shown in fig. 8.

Test course 7

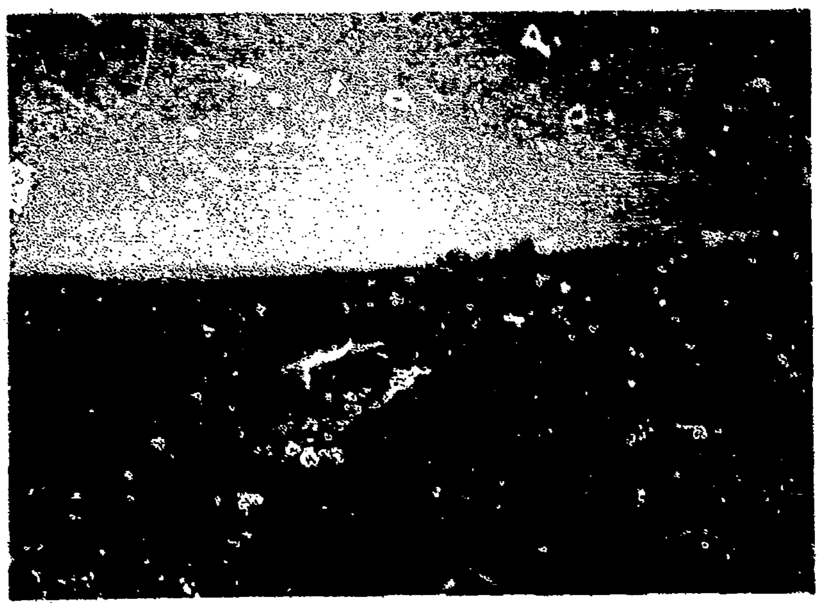
16. Test course 7 was located at Dunns Corner, about 18.4 miles south, 32 deg east of the headquarters complex of CFB Gagetown (see fig 2). The length of this test course is only 500 ft. The test course was in a general maneuver area and ran parallel to a frequently used tank trail. The average topographic slope of the test course was 16.2 percent. Surface irregularities were almost insignificant, approach angles were less than 30 deg, step heights were less than 8 in., and there was no obvious pattern to the irregularities. The soil was clayey fine sand (ML), the average cone index of both the 0- to 6-in. and 6- to 12-in. layers was greater than 300. The vegetation of the test course was short grass. Test course 7 is shown in fig. 9.

Test course 8

17. This test course was an abandoned ski slope located on Cootes Hill, about 20.4 miles south, 23 deg east of the headquarters complex, CFB Gagetown (see fig. 2). The total length of the test course was 1600 ft.



a. Looking north



b. Looking south

Fig. 8. Test course 6

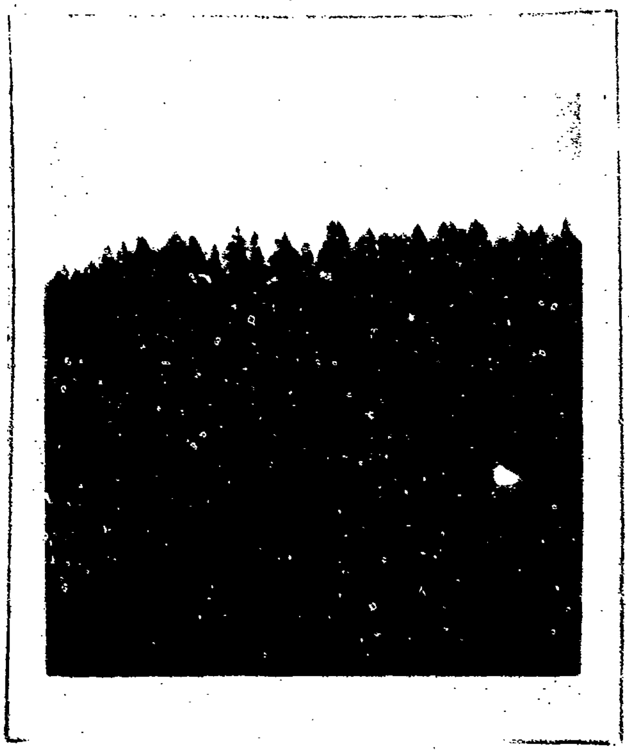


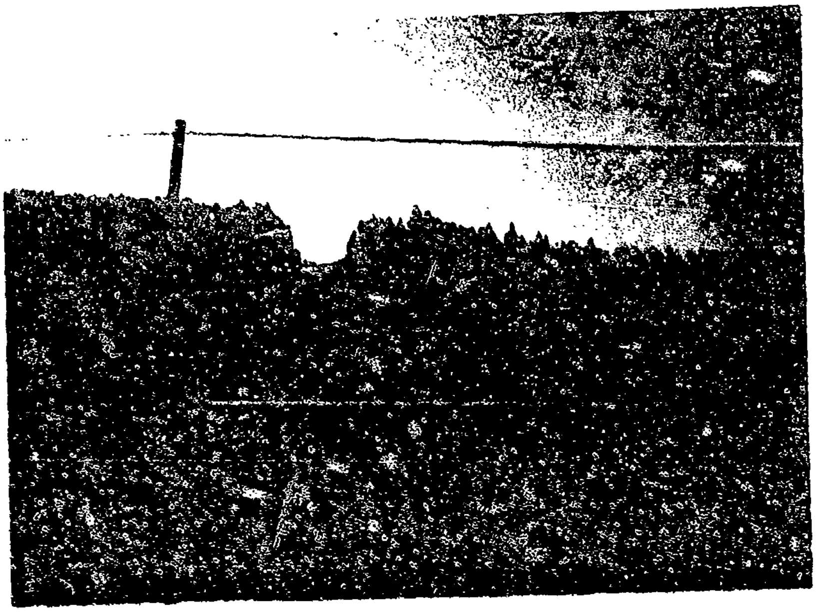
Fig. 9. Test course 7

The vegetation along the test course was dense scrub about 5 ft tall; therefore, ground visibility was extremely poor over about 60 percent of the test course. However, visibility was good over the rest of the course. The depth to bedrock ranged from 3 to 18 in. The soil over the bedrock was silty sand (SM). The average cone index of both the 0- to 6-in. and the 6- to 12-in. layers was greater than 300. The average topographic slope was 18.4 percent. The only significant surface irregularities were boulders or outcropping rocks. The boulders had approach angles greater than 45 deg; they were approximately 10 to 12 in. high and were spaced greater than 100 ft apart. In the summer of 1968 the area was being used for general maneuver purposes. Test course 8 is shown in fig. 10.

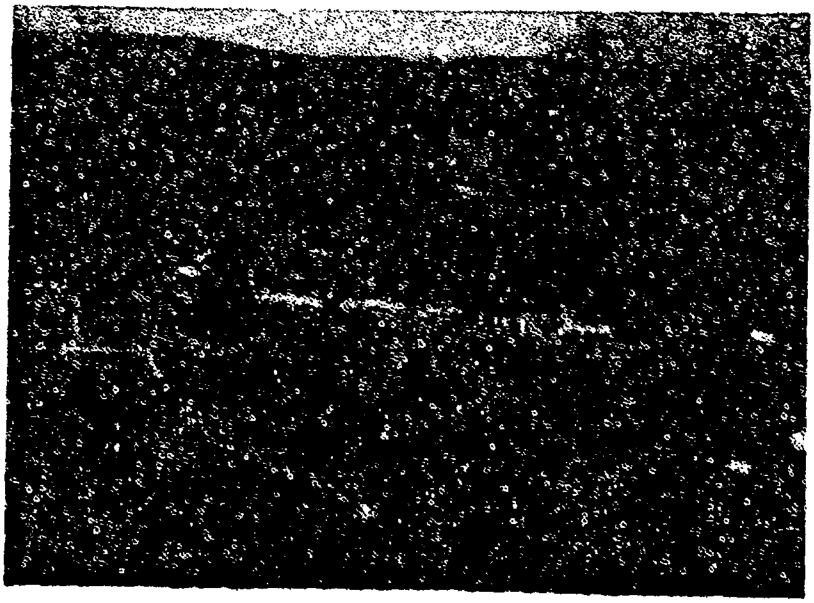
The Test Vehicle

18. The nomenclature of the test vehicle is: Truck, Tank: fuel-servicing, 2500-gallon, 4x4, XM559E1.* It is one of the GOER family of vehicles. The vehicle was developed to fulfill an urgent requirement for a medium capacity, refueling vehicle and liquid fuel transporter with off-road characteristics superior to those possessed by conventional wheeled vehicles. It was intended to be used as a distribution vehicle in combat and rear areas to refuel simultaneously several tactical and/or administrative vehicles. The general design guidelines specified that the vehicle was to have typical GOER characteristics (e.g., maximum off-road mobility corresponding to that of the tactical units to be supported and inherent swimming capabilities without any special preparation). Also the GOER 2500-gallon tanker was to be air and rail transportable without major disassembly. The test vehicle is shown in fig. 11.

* Information taken from characteristics sheet furnished by the U. S. Army Tank-Automotive Command.



a. Looking from west to east



b. Looking from east to west

Fig. 10. Test course 8

Fig. 11. The 8-ton XM559-E1 GOER

Pertinent vehicle characteristics

19. The physical characteristics of the vehicle that are pertinent to the application of the WES analytical model for predicting vehicle performance are tabulated below:

Physical Characteristics	
Cross-country weights, lb	
Gross	45,770
Payload	16,850
Dimensions	
Overall length (including winch if available), in.	394.6
Height of leading edge, in.	42.1
Width, in.	112.0
Distance between axles, in.	235.0
Center of gravity location of full load	
Horizontal distance from front axle	Not available
Vertical distance aboveground	Not available
Approach angle, deg	35
Departure angle, deg	37
Undercarriage clearance, in.	
Axle	23.3
Interior	29.3
Force leading edge can withstand, lb	Not available
Tire data	
Type	Off highway
Size	18.00x33
Ply	10
Tread design	Modified traction
Unloaded diameter (excluding tread), in.	69.0
Tire width, in.	18.0
No. of wheels	4
No. of tires	4
Cross-country inflation pressure (CCP), psi (approx)	30
Cross-country tire deflection, %	25
Mechanical Characteristics	
Engine	
Make	Caterpillar
Model	D333TA
Fuel type	Diesel
Horsepower (brake or net)	Net 176
Engine rpm at brake horsepower	2200
Maximum torque (gross or net), ft-lb	Net 494
Engine rpm at maximum torque	1580

Mechanical Characteristics (Continued)

Transmission	
Make or model	Caterpillar power shift with torque converter
Ratios	
1st	4.274
2nd	2.463
3rd	1.885
4th	1.418
5th	1.087
6th	0.818
Transfer case	
Make or model	Caterpillar DV-2
Ratio	
Low	None
High	1.222
Axles	
Make or model	Caterpillar
Ratio	14.659
Winch capacity, lb	10,000
Steering data	
Turning radius (over bumper), ft	26.7
Maximum steering angle, deg	60.0
Time required to steer from straight-ahead position to full lock turn, sec	3.0
Articulation	
Maximum pitch angle, deg	0.0
Maximum roll angle, deg	Not available
Brakes	
Type	Cam-actuated shoe
Drum size, in.	20.25
Deceleration rate estimated, g	0.6

Vehicle performance relations

20. It is necessary to obtain certain vehicle performance relations before the analytical model can be applied to the problem of performance predictions. The relations that were used to predict the performance of the 8-ton XM559E1 GOER are discussed in the following paragraphs.

21. Force-speed relation. The force referred to here is tractive force. In theory, tractive force is equal to the total torque (in

foot-pounds) input at the axles divided by the rolling radius (in feet) of the wheel. Speed is the rotational speed of the wheels and is obtained by use of the following equation:

$$S = 0.6818 \times rps \times 2\pi r$$

where

S = wheel rotational speed, mph

0.6818 = the factor for converting fps to mph

rps = wheel revolutions per sec

r = rolling radius of the wheels, ft

The force-speed relation is a function of (a) the power (torque and rpm) output of the engine, (b) the total gear reductions, (c) the rolling radius of the wheels, and (d) the efficiency of the power train. The force-speed relation that was used to predict the performance of the XM559E1 GOER is given in fig. 12. The data from which the curve was developed were obtained from Developments and Proof Services (D and PS) of Aberdeen Proving Ground (APG), Maryland.

22. Force-deflection relations of the tires. The force referred to here is wheel load or vertical force (in pounds) applied to the tire through the axle; this vertical force includes the weight of the wheel. Deflection is the difference between the unloaded and loaded cross-section heights of the tire. Since the design of all the tires that were on the XM559E1 GOER at the time of testing was the same, only one force-deflection relation was considered necessary. The force-deflection relation that was used in predicting the performance of the XM559E1 is shown in fig. 13. The part of the relation shown by a solid line was

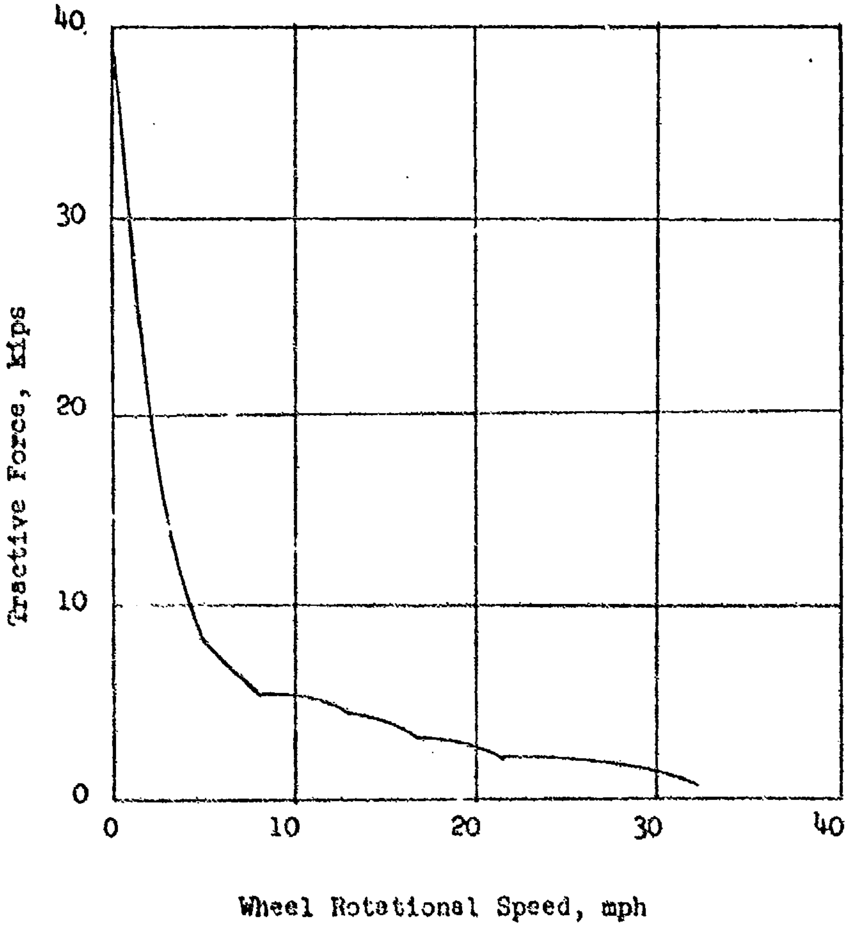


Fig. 12. Force-speed relation of the XM559 GOER

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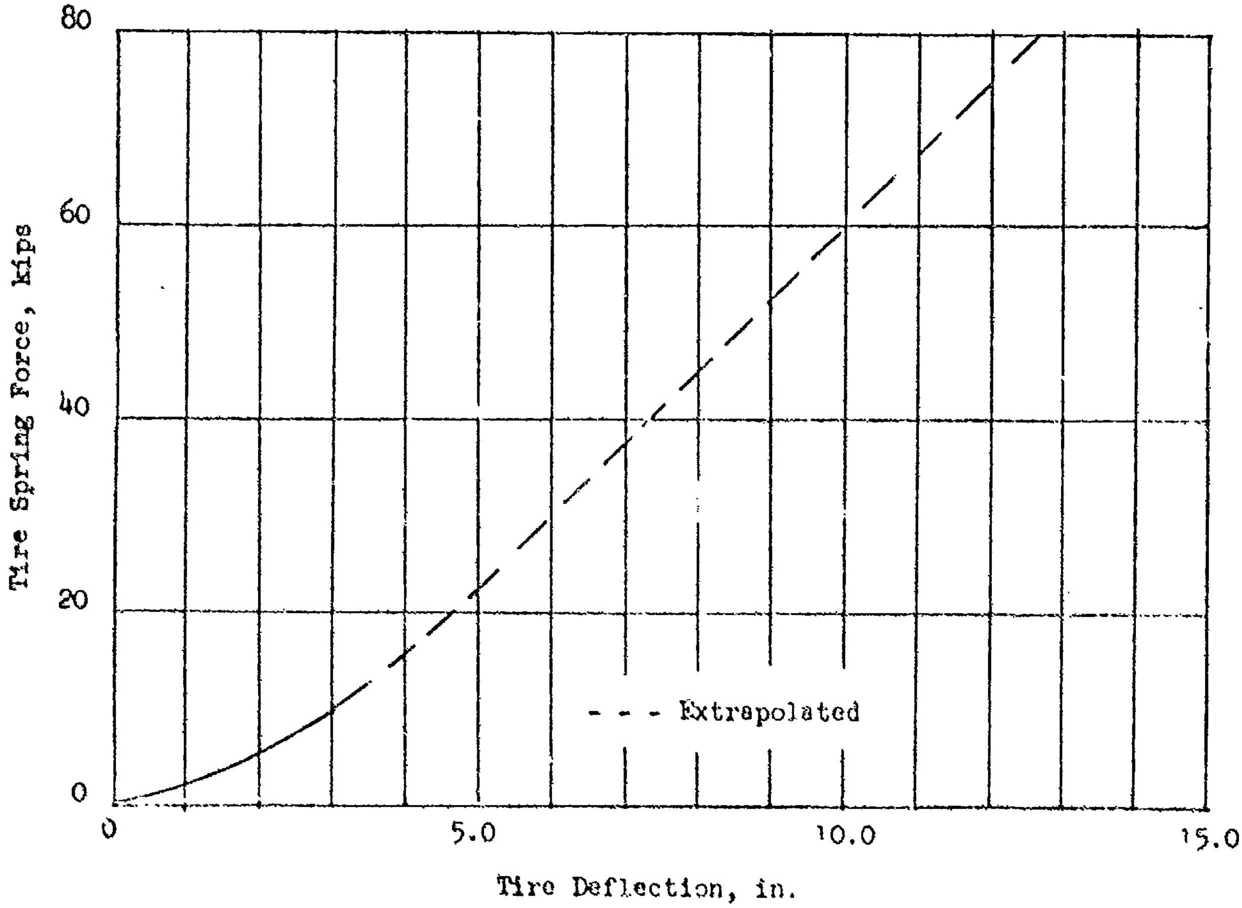


Fig. 13. Force-deflection relations used for XM559 tire

measured by WES personnel and that part shown as a broken line was extrapolated.

23. Force-deflection versus velocity relation of the tire (damping). The damping factor used for the GOER tire was 40 lb of vertical force for each 1 in. per sec of deflection rate. This value (40 in. lb/sec) was obtained from tire data available at the WES.

Test Procedures and Data Collected

Speed tests

24. Speed test procedure was as follows:

a. The vehicle was positioned at a distance sufficient to enable the driver to attain a constant speed before entering the test course.

b. The entire measurement and recording (instrumentation) system was checked and all calibrations necessary to interpret an oscillogram were recorded.

c. The driver was instructed to maintain the maximum safe speed throughout the test course.

d. When the front bumper of the vehicle crossed the starting point of the test course, an event was recorded on the oscillogram.

e. When the front bumper crossed the end of the test course, an event was recorded on the oscillogram.

f. The position of the vehicle was marked and an event was recorded on the oscillogram simultaneously at from 2- to 5-sec intervals during tests. The time intervals were controlled by the judgment of the instrument operator.

A summary of the results of the speed tests is given in table 1.

Drawbar pull-slip tests

25. The drawbar pull-slip test procedure was as follows:

a. The test vehicle was checked to ensure that it was in good mechanical condition.

b. The tire inflation pressure was adjusted to 30 psi.

c. The test vehicle was positioned with the load vehicle (a Centurion tank) directly behind it on the surface to be tested.

d. A dynamometer was installed in the towing cable and the cable ends were attached to the test vehicle and the load vehicle.

e. The instrumentation system was checked and the necessary calibrations were recorded.

f. Once the vehicles were ready and in position, the test and load vehicles attained a steady state of motion (approximately 2 mph), and a load was applied slowly by varying the speed or applying the brakes of the load vehicle until the maximum drawbar pull was attained. By coordination between the engineer and the load vehicle operator, a steady load was held for approximately 5 sec. This procedure was repeated several times to ensure that the data obtained were reliable.

The drawbar pull-slip test were conducted at the south end of test course No. 6, in an area where the surface was level (see table 1 for cone index data). The results of the drawbar pull-slip tests are summarized in table 2.

Towed tests

26. The towed test was conducted in the same area (test course 6) in which the drawbar pull-slip tests were conducted to determine the resistance to towing. Towed test procedures were as follows:

a. The test vehicle was prepared in the same manner as that used for the drawbar pull-slip tests with reference to mechanical condition and tire pressure.

b. Test site requirements were the same as those for the drawbar pull-slip tests.

c. The towing vehicle (a Centurion tank) was attached to the test vehicle by means of a cable and a dynamometer.

d. The instrumentation system was checked and the necessary calibrations were recorded.

e. The vehicle was towed in a straight line at a constant speed of about 2 mph.

The average resistance to towing was 3500 lb on a level surface where the cone index was greater than 300.

Free-rolling motion resistance test

27. One free-rolling motion resistance test was conducted to determine the vehicle's resistance to motion when rolling with the brakes off and the power train disengaged on the secondary road (test course number 1). This test was conducted in the following manner:

a. The vehicle was positioned in the center of the road on a 3-deg slope, the power train was disengaged, and the brakes released, allowing the vehicle to roll freely down the hill.

c. The distance the vehicle moved forward was measured relative to time.

The free-rolling vehicle accelerated at an average rate of 0.94 ft/sec^2. The motion resistance was computed by use of the following equation:

$$F = \frac{W}{g} a$$

where

F = the force acting to accelerate the vehicle

W = gross vehicle weight, 45,770 lb

a = vehicle acceleration, 0.94 ft/sec^2

g = acceleration due to gravity, 32.18 ft/sec^2

now

$F = W \sin \theta$ - motion resistance

where

θ = angle of the surface of the ground from the horizontal, 3 degs

therefore

$$W \sin \theta = 45{,}770 \times 0.0523 = 2{,}394 \text{ lb}$$

If all the known values are substituted into the original equation the results are:

$$2{,}394 - \text{motion resistance} = \frac{45{,}770}{32.18} \times 0.94$$

then

motion resistance = 1,057 lb and is valid for the vehicle on level ground.

Terrain data collected

28. When pertinent, the following terrain data were collected for each test course.

29. Cone index and remolding index. A sufficient number of cone index measurements were made at appropriate horizontal intervals to adequately describe the soil strength within the test course. Measurements were made at the surface, at 1-in. vertical increments to a depth of 6 in., and then at 3-in. vertical increments to a depth of 24 in. or to bedrock. No remolding data were obtained because the mineral soils were too firm for remolding, and remolding data were not desired for organic soils (muskeg). Cone index data are summarized in table 1.

30. Bulk samples. Representative bulk soil samples were obtained from each test course for the purpose of classification.

31. Vegetation data. When pertinent, a sufficient number of vegetation samples were taken at appropriate locations to adequately describe the vegetation structure. The data included the designation of vegetation spacing and stem diameter. These data are summarized in table 1.

32. Visibility. When pertinent, visibility data were taken by the pattern recognition method* to determine the degree of obscuration by trees and appurtenant foliage. These data are summarized in table 1.

33. Surface geometry profiles. Surface geometry gross profiles were run to a specified 6-in.-contour accuracy along the path of the vehicle over the entire test course, using conventional surveying techniques In addition to the gross profiles, surface geometry profile

* U. S. Army Engineer WAterways Experiment Station, CE, "A Quantitative Description of Camp Petawawa (Canada), Terrainfor Ground MObility," (in preparation).

samples about 100 ft long were collected to an accuracy of 1-in.-elevation change at two or three points along the test course. These data were reduced to an approach angle and a step height to represent the test course. These values are given in table 1.

34. Supplementary data. Supplementary data, such as land-use, vegetation, topographic position, etc., were collected. A sample of the form used to record these data is given in fig. 14.

35. Photographs. Appropriate photographs were taken of each test course and of predominant characteristics of the terrain pertinent to the test program.

Vehicle performance data collected

36. When pertinent, the following vehicle performance data were collected for each test.

37. Time. Time was continuously recorded for all speed tests and for the free-rolling motion-resistance test at intervals of 0.5 sec.

38. Distance. The location of the test vehicle was marked simultaneously on the ground and the oscillogram from 2- to 5-sec intervals during the speed tests. After the speed test, the distances between the location marks were measured.

a. During the drawbar pull-slip test, the towed test, and the free-rolling motion resistance test, the forward movement of the vehicle was measured by means of a wire play-out line.

b. Wheel rotation distance was measured to an accuracy of

Supplementary Site Data

ite No. ______________ Location: ________________________________

Sampling Team: ____________________________________ Page _____ of _____

Land Use (Select as many as required to describe condition: circle appropriate terms.)

1. Not obviously used by man or domestic animals. Undisturbed.
2. Obviously used by man or domestic animals.
   - a. Cropland currently in use (excluding hayfields, orchards, vineyards, tree plantations). Type ______________
   - b. Cropland currently lying fallow (excluding hayfields, orchards, vineyards, tree plantations). Type ______________
   - c. Area grazed by domestic animals
   - d. Hayfields (not currently being grazed)
   - e. Orchards, vineyards, tree plantations. Type ______________
   - f. Lawns, recreation areas
   - g. Logged, cut for fuel, newly cleared for slash-and-burn agricultu

Depth of water over soil surface (if any): ______________

Depth below surface of free water (if any): ______________

Depth to bedrock (if any): ______________

Vegetation (select one, if possible. If a choice between two is difficult, indicate both.)

1. Forest	5. Tall scrub woodland	9. Tall-grass prairie
2. Woodland	6. Tall scrub savanna	10. Short-grass prairie
3. Savanna	7. Low scrub	11. Barren
4. Tall scrub forest	8. Low scrub savanna	

Maximum topographic slope: ______________

Topographic position: ______________

Profile Sketch

WES Form No. 1419
June 1964

Fig. 14. Sample of form used to record supplementary data

one-sixth of a revolution during the drawbar pull-slip tests.

39. Accelerations. Two accelerometers were mounted under the driver's seat of the vehicle. During all speed tests, acceleration in the vertical and longitudinal directions was continuously recorded on the oscillogram.

40. Events. An event was marked on the oscillogram each time the position of the vehicle was marked.

41. Supplementary data. An on/off switch was installed under the throttle pedal and attached to the oscillograph for the purpose of recording on the oscillogram whether or not the driver was operating the vehicle at full throttle.

a. Other supplementary data such as the driver's instructions, driver's comments after test, and general notes pertinent to the test were recorded by the test engineer.

b. Photographs relative to vehicle performance were made both during and after tests, when possible.

PART III: PERFORMANCE PREDICTIONS AND EVALUATIONS

42. The procedures for predicting vehicle performance vary with the general characteristics of the terrain; for instance, the part of the model that predicts the effects of trees on the performance of the vehicle was omitted if there were no trees on the test course.

Predicted Vehicle Performance on Secondary Roads

43. The surface of the secondary road test course (test course 1) was smooth, firm, and devoid of vegetation; therefore the effects of vegetation, visibility, surface roughness, and soil strength were deleted from the predictions.

44. When the engine of the XM559E1 is turning at its maximum (governed) speed as it would probably be when the vehicle is traveling downhill and the force of gravity is greater than the motion resistance of the vehicle, the predicted vehicle speed was computed by use of the following equation:

$$S_{max} = 0.6818 \times \frac{rpm_{max}}{60} \times \frac{1}{T_R \times TC_R \times D_R} \times R_c$$

where

S_{max} = the maximum predicted speed, mph

0.6818 = the factor for converting fps to mph

rpm_{max} = the governed maximum rpm of the vehicle's engine, listed as 2200 on characteristic data sheet (ATAC)

T_R = transmission gear ratio. In this case the vehicle is operating in 6th gear (0.818 to 1)

TC_R = gear ratio of the transfer case. In this case the vehicle is operating in high range (1.222 to 1)

D_R = gear ratio of the axle differential (14.659 to 1)

R_c = the rolling circumference, ft, of the wheels at the specified inflation pressure (30 psi). This value was measured to be 18.016 ft.

Now substituting in the equation above

$$S_{max} = 0.6818 \times \frac{2200}{60} \times \frac{1}{0.818 \times 1.222 \times 14.659} \times 18.016$$

$$S_{max} = 30.74 \text{ mph}$$

Therefore, it was predicted that the XM559E1 would travel at a maximum speed of 30.74 mph when traveling downhill on the secondary road test course.

45. When the XM559E1 is traveling uphill or upslope and the engine is operating at its maximum power output, the vehicle performance relations and the terrain-vehicle relations necessary to predict its maximum speed are:

a. The performance of the engine and power train in terms of tractive force versus speed. This information was obtained from Development and Proof Services, Aberdeen Proving Ground, Md., and is shown graphically in fig. 12.

b. The free-rolling motion resistance of the vehicle on a surface comparable to that of the test course. Free-rolling motion resistance was measured to be 1057 lb (see paragraph 27).

c. The force due to gravity acting to retard the motion of the vehicle. This force was computed by use of the equation:

$$F_G = W \sin \theta$$

where

F_G = force due to gravity, lb

W = gross weight of vehicle, lb

θ = slope or angle of the surface of the ground from the horizontal

46. A sample graphical solution of a prediction of XM559E1 speed when traveling upslope on test course 1 is shown in fig. 15. The average slope of this section of the test course was 8.22% or 4.7 deg; therefore, the force due to gravity was

$$F_G = 45{,}770 \sin 4.7$$

$$F_G = 45{,}770 \times 0.082$$

$$F_G = 3753 \text{ lb}$$

The motion resistance of the vehicle on the level surface was 1057 lb. Therefore the total terrain force requirement was 3753 + 1057 = 4810 lb. The speed on the force-speed relation curve that corresponds to 4810 is 12.3 mph, the predicted speed.

47. The average speed predicted for the secondary road test course (test course 1) was obtained by use of the following equation:

$$\text{Average speed} = \frac{\text{total distance}}{\frac{\text{distance downslope}}{\text{speed downslope}} + \frac{\text{distance upslope}}{\text{speed upslope}} + \frac{\text{distance on level}}{\text{speed on level}}}$$

The predicted average speed and the actual average test speeds are given in table 1.

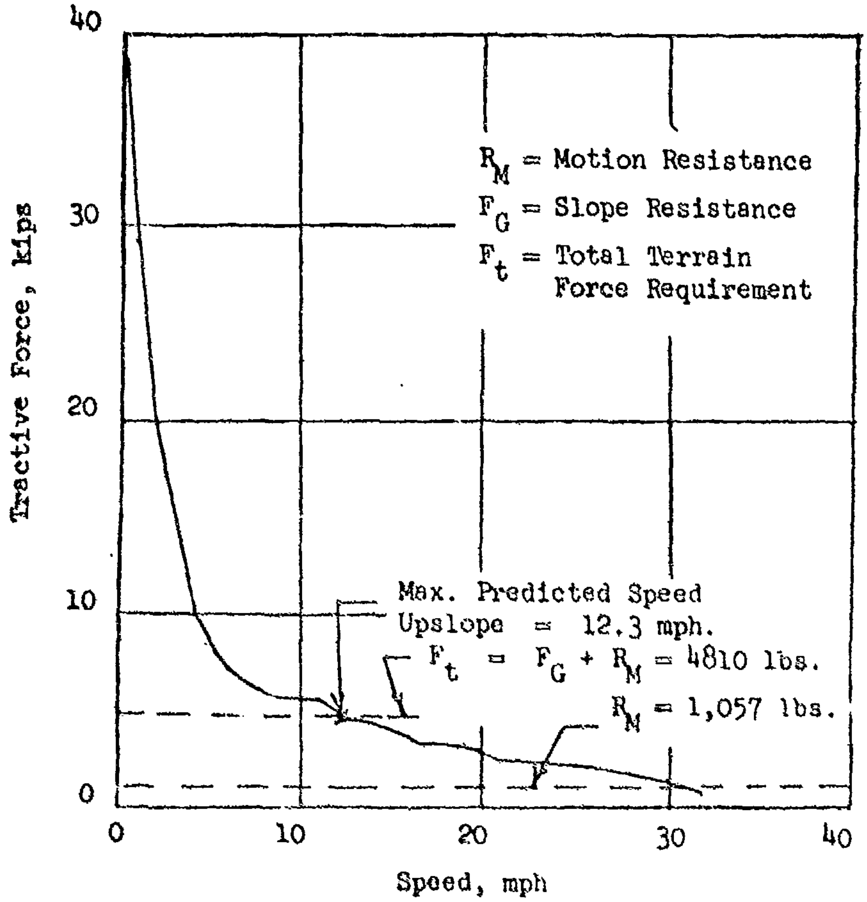


Fig. 15. Prediction of XM559E1 speed on secondary road, speed test 1

Predicted Vehicle Performance in Cross-Country Environment

48. When predicting first-pass speed performance of the XM559 E1 in the Canadian terrains tested, the terrain-vehicle relations considered were:

a. The effects of strength of surface material on vehicle performance

b. The effects of surface geometry on performance

c. The effects of vegetation on performance.

The terrain-vehicle relations required to predict first-pass speed performance and the acquisition of and/or the procedures used in developing these relations are discussed in the following paragraphs.

Effects of strength of surface material on vehicle performance

49. To determine vehicle performance on smooth, natural soils on level terrain, the following relations must first be known:

a. One-pass vehicle cone index compared to soil strength

b. Motion resistance versus soil strength

c. Tractive force-slip relations for the pertinent soil strength

These relations plus the engine-power train performance of the vehicle in terms of tractive force and speed (see fig. 12) can then be used to determine the performance of the vehicle on smooth, level terrain.

50. One-pass vehicle cone index. Uniform surface materials having low mass strengths allow vehicle tractive elements to sink into the material, causing a high resistance to motion. Also a vehicle's ability to develop tractive force is greatly reduced when operating on low strength materials. The one-pass vehicle cone index is the minimum soil

strength on which the vehicle can operate and barely maintain forward motion. The physical vehicle characteristics used and the method of relating these characteristics for use in determining the mobility index of wheeled vehicles are given in fig. 16. After computing the mobility index, the 50-pass vehicle cone index can be determined by use of table 3. One-pass vehicle cone index is taken to be one-half of the 50-pass vehicle cone index value. If the average cone index of the surface material is less than the one-pass vehicle cone index of the vehicle, then zero speed is automatically predicted for the terrain complex or test course.

51. Motion resistance. Even if a vehicle is not immobilized in soft soil, the vehicle's motion resistance is greatly influenced by the strength of the soil, thus influencing the vehicle's ability to obtain and maintain speeds. The WES has an acceptable method of relating wheel parameters and soil strength parameters for the purpose of estimating motion resistance; however, for the purpose of predicting the performance of the XM559E1 in all the Canadian test courses except the secondary road and the muskeg test courses, the results of the towed motion resistance tests (see paragraph 26) were used (i.e. motion resistance = 3500 lb).

52. Tractive force-slip-soil strength relations. The tractive force-slip relations used to predict speeds in all test courses except the secondary road and the muskeg test courses were determined from the results of the drawbar pull-slip tests and the towed motion resistance tests that were conducted as a part of the Canadian test program. The results of these tests are shown in fig. 17. Tractive force is shown on the vertical axis; these values were obtained by adding drawbar pull and the average towed motion resistance. Percent wheel slip is shown on

(1)	Contact pressure factor	=	$\dfrac{\text{gross weight, lb}}{\text{tire width, in.} \times \dfrac{\text{outside diam of tire, in.}}{2} \times \text{No. of tires}}$		=	18.42

Weight Range, lb $\left(\dfrac{\text{Gross vehicle wt, lb}}{\text{No. of axles}}\right)$	Weight Factor Equations
< 2000	Y = 0.553X
2000 to 13,500	Y = 0.033X + 1.050
13,501 to 20,000	Y = 0.142X − 0.420
> 20,000	Y = 0.278X − 3.115

(2) Weight factor = (table above); $X = \dfrac{\text{gross vehicle wt, kips}}{\text{No. of axles}}$, Y = weight factor = 3.28

(3)	Tire factor	=	$\dfrac{10 + \text{tire width, in.}}{100}$	=	$\dfrac{10 + 18}{100}$	=	0.28
(4)	Grouser factor	=	With chains = 1.05 Without chains = 1.00			=	1.00
(5)	Wheel load factor	=	$\dfrac{\text{gross weight, kips}}{\text{No. of wheels}}$ (duals counted as one)		$\dfrac{45.770}{4}$	=	11.44
(6)	Clearance factor	=	$\dfrac{\text{Clearance, in.}}{10}$	=	$\dfrac{30}{10}$	=	3.00
(7)	Engine factor	=	>10 hp/ton = 1.00 <10 hp/ton = 1.05			=	1.00
(8)	Transmission factor	=	Hydraulic = 1.00 Mechanical = 1.05			=	1.00

$$\text{Mobility index} = \left(\frac{(1) \times (2)}{(3) \times (4)} + (5) - (6)\right) \times (7) \times (8)$$

$$\text{Mobility index} = \left(\frac{18.42 \times 3.28}{0.28 \times 1.00} + 11.44 - 3.0\right) \times 1 \times 1$$

Mobility index	=	224
Fifty-pass vehicle cone index	=	127
One pass vehicle cone index	=	63

Fig. 16. Mobility index for self-propelled wheeled vehicle in fine grained soils. 8-ton XM559E1 GOER, 45,770 lb, 18.00x33 special GOER tire

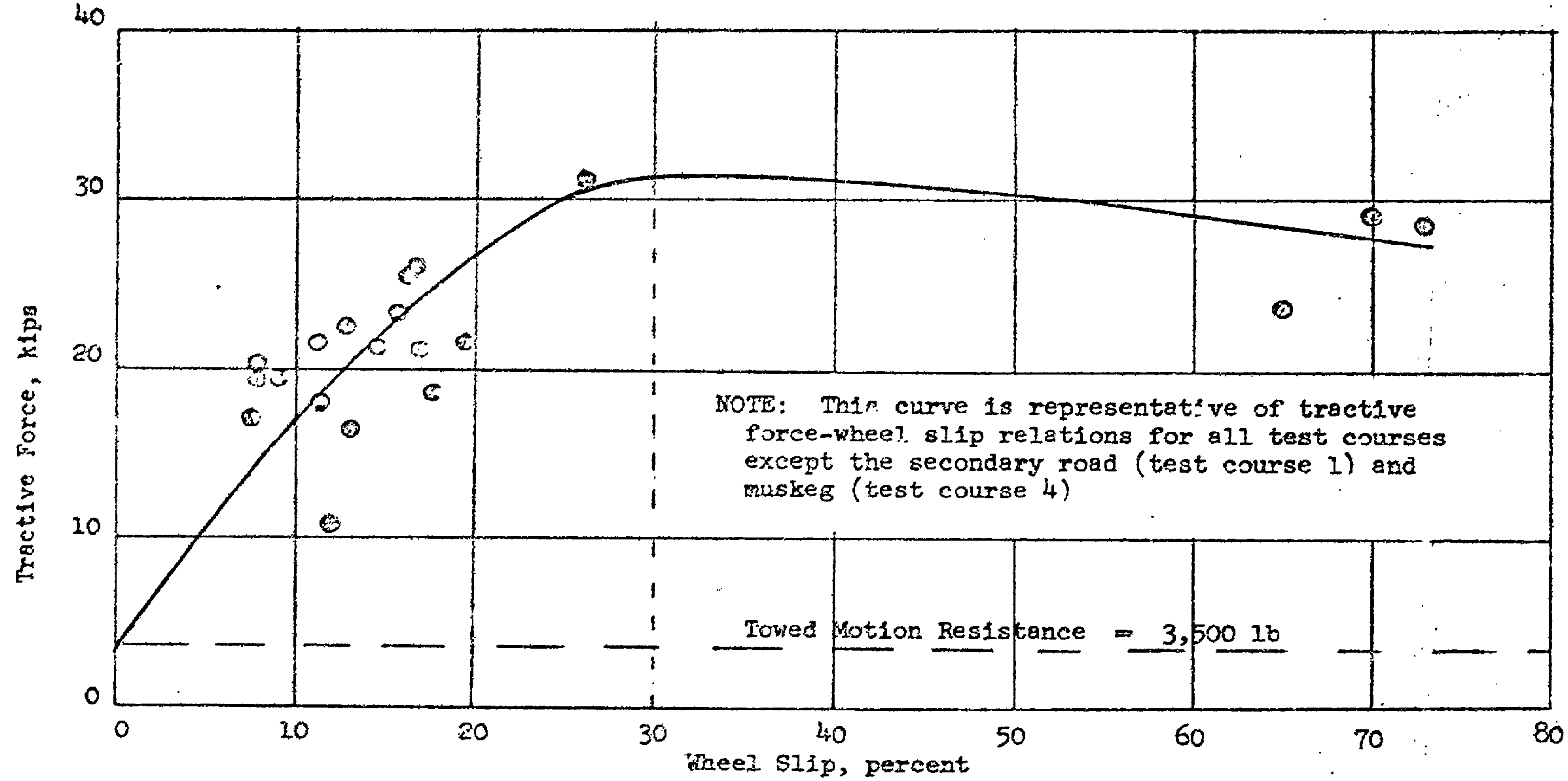


Fig. 17. Traction-slip relations for XM559

the horizontal axis; this value was computed by use of the following equation:

$$\% \text{ slip} = \frac{(\text{wheel rotational distance}) - (\text{vehicle ground distance})}{\text{wheel rotational distance}} \times 100$$

53. Performance of the XM559E1 on smooth, level soil. One tractive force-wheel slip relation was used in the prediction of XM559E1 speeds for test courses 2, 3, 5, 6, 7, and 8 because at the time the tests were conducted the surface soils on these courses were dry and firm. The soil-vehicle performance relation used for these courses was discussed in paragraph 52.

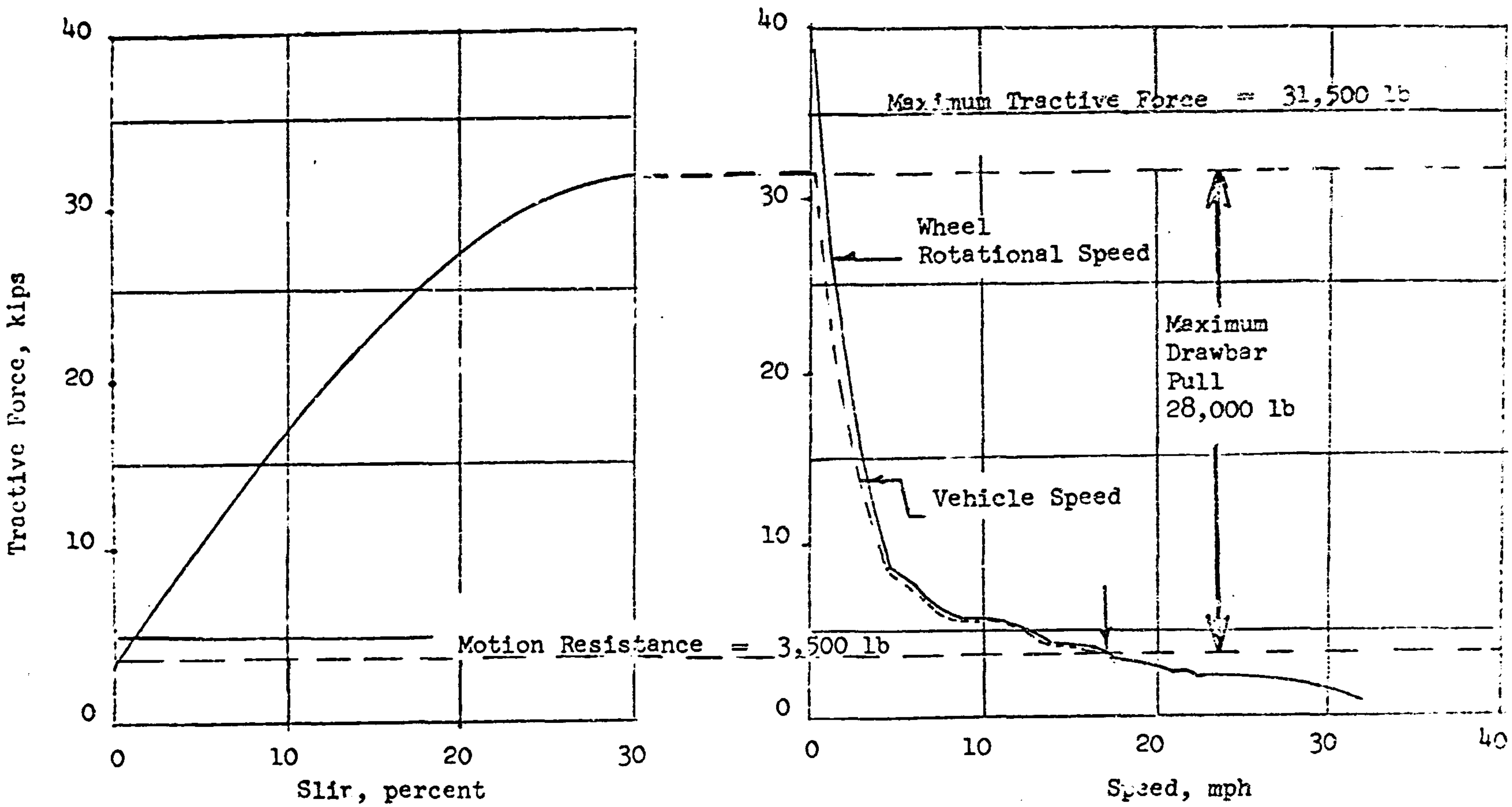
a. The basic relations needed to describe the performance of the vehicle on smooth, level soil are:

(1) The tractive force-slip relation from near zero percent slip to the percent slip where maximum tractive force is obtained. This section of the relation was taken from fig. 17 and is reproduced in fig. 18a.

(2) The relation of maximum sustainable tractive force to the sustained rotational wheel speed. This relation is shown by the solid line in fig. 18b.

(3) The total resistance to motion when the vehicle is towed at a constant speed on the smooth, level surface. This value is shown as a horizontal broken line drawn across the lower part of fig. 18a and b.

b. The tractive force-vehicle speed relation for the soil condition tested is shown by the dashed line in fig. 18b.



a. Traction-slip relations

b. Traction-speed relations

Fig. 18. Performance of XM559 on smooth, level soil

This line was drawn by reducing the speeds shown by the solid line according to the tractive force-slip relations shown in fig. 18a.

Effects of surface
geometry on vehicle performance

54. The effects of surface geometry on vehicle performance are considered under two headings: (a) the effects of slope on vehicle performance and (b) the effects of surface irregularities on vehicle performance. The methods of determining these effects are discussed in the following paragraphs.

55. Effects of slope on vehicle performance. Gravity acting on the mass of the vehicle is a propelling force when the vehicle travels downslope, and conversely is a resisting force when the vehicle travels upslope. The magnitude of the force of gravity is computed using the equation

$$F_G = \pm W \sin \theta$$

where

F_G = the force of gravity acting on the vehicle

W = the gross weight of the vehicle

θ = the angle at which the surface is inclined from the horizontal

The positive sign is used when the vehicle is traveling upslope and the negative sign is used when the vehicle is traveling downslope.

56. Effects of surface irregularities on vehicle performance. The surface geometry profile data were reduced to a representative approach angle θ and step height H (see fig. 19a). The approach angles and

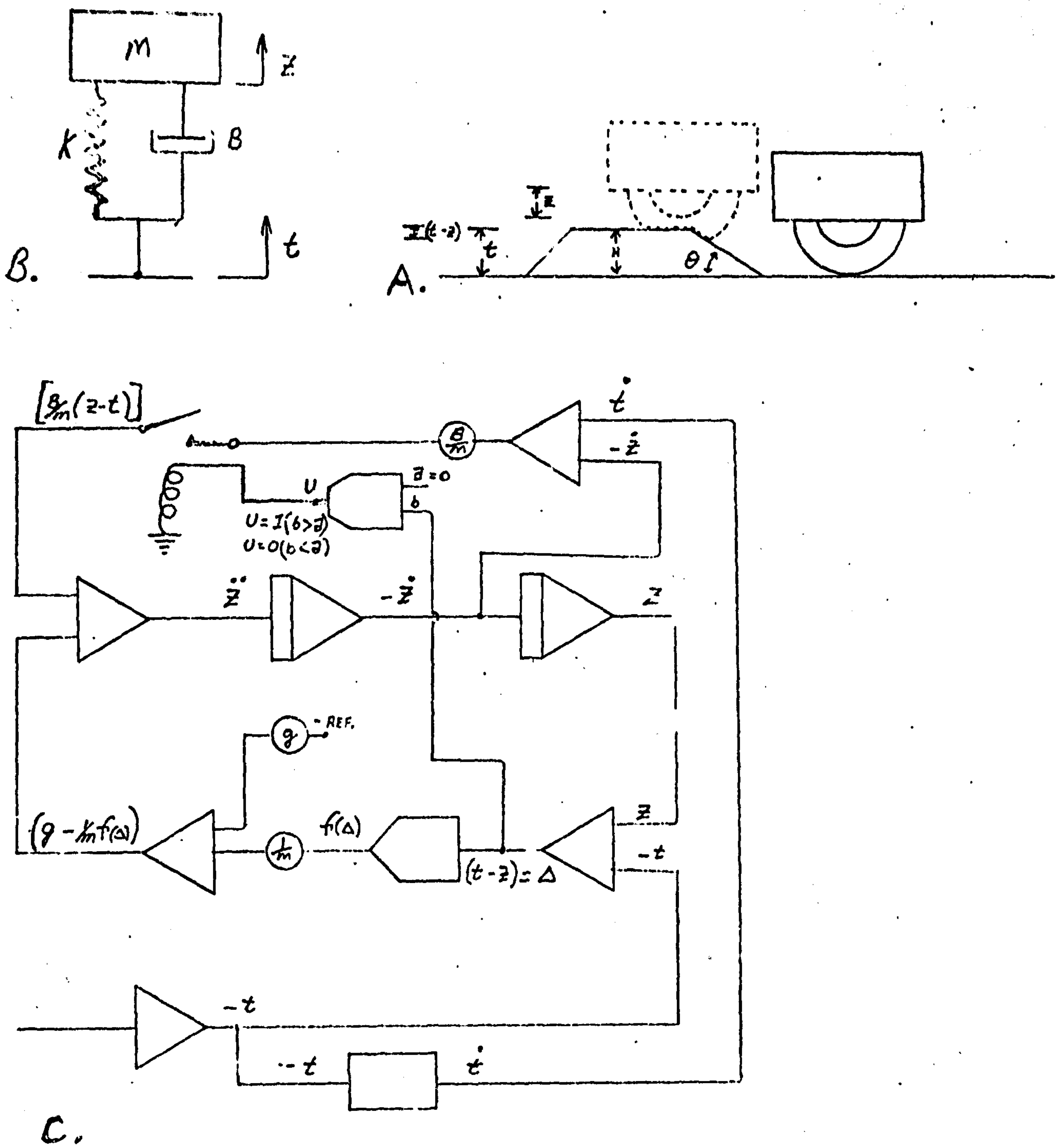


Fig. 19. Analog Simulation of XM559E1 Performance

step heights selected to represent the test course were the average of the most critical irregularities. The irregularities did not fit into any pattern of spacing; however they were significantly numerous to justify the assumption that the speed over the entire test course would be limited to the safe speed at which a single irregularity could be crossed.

57. The speeds at which the XM559E1 should traverse the critical irregularities were determined by the use of a simplified mathematical model. This model consisted of one mass which approximated the vehicle wheel load, one spring represented by the appropriate tire load-deflection curve, and one damper which was an approximation of the vehicle's tire and structural damping. This single degree of freedom model was considered applicable because the XM559E1 has no springs or shock absorbers, the wheel base is exceptionally long which minimized pitch motion contribution to driver seat acceleration (for obstacles considered) and the driver's seat (the point of interest) is located almost directly above the front axle (see fig. 11).

58. The equation of motion for the model of the XM559E1, displayed schematically in fig. 19b, is as follows:

Vertical motion (bounce):

$$M\ddot{z} = k\Delta + b\dot{\Delta} - Mg$$

where

$k \geq 0$; i.e. the model is not restricted to follow the terrain and the tire cannot exert negative (downward) force.

$b = 0$ when $(t-z) \geq 0$, i.e. damping forces do not affect motion when tire is off the terrain.

$k = f(\Delta) = f(t-z)$

The graphic diagram used for analog computer simulation of the model is presented in fig. 19c. Symbology used in this diagram and the preceding schematic is as follows:

$\ddot{z}, \dot{z}, z$ = Vertical motions above axle (acceleration, velocity and displacement respectively).

t = Terrain forcing function

k = Tire spring, determined from static load deflection tests.

b = Damping coefficients

M = Vehicle's wheel load (mass)

g = Acceleration due to the earth's gravitational field

Δ = Tire deflection $\left((t-z) \leq 0\right)$

59. After the test courses were classified on the basis of an approach angle and a step height, the analog simulation was run for different speeds until an acceleration of approximately 2.5 g was recorded. This process was repeated for each test course. The speed at which 2.5 g was recorded was determined to be the maximum predicted speed that the vehicle should travel through the test course. In one case (test course No. 5) the computer model was run for 8 and 10 ft/sec and predicted 2 and 3 g's, respectively; therefore, the predicted speed was linearly extrapolated to be 9 ft/sec. The results of the computed response of the XM559E1 in test courses 2, 5, 6, and 8 are shown in fig. 20.

Effects of vegetation on performance

60. Trees, stumps, and logs are deterrents to vehicle performance in that the vehicle must slow down to maneuver or override them. Which vegetation features should be overridden or circumvented are not always obvious. Accordingly, speed predictions are made by gradually increasing the size of the stems that should be overridden, thus reducing the maneuver

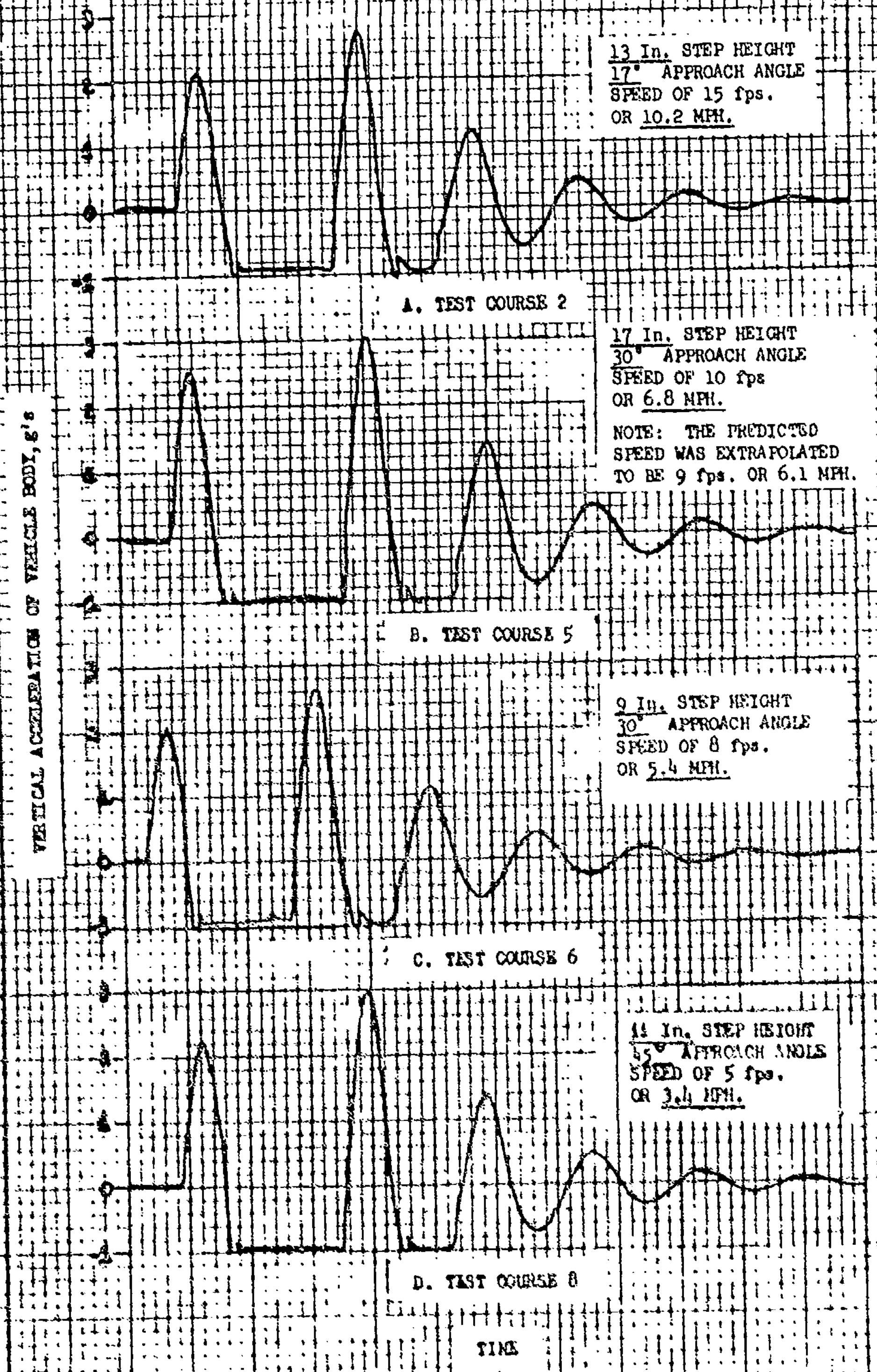


Fig. 20 RESULTS OF ANALOG COMPUTER ANALYSIS OF XM 559's RESPONSE TO SMALL SURFACE IRREGULARITIES

requirements until the best average speed is achieved for the terrain situation under consideration.

61. The analytical model considers vegetation in terms of (a) average and maximum forces required to override trees, (b) the need to maneuver around trees, and (c) the amount the drivers vision is obscured by plants.

62. Average force required to override multiple stems. The average force required to override multiple stems was determined by equations derived from empirical relations established from field test results. The parameters used in deriving the relations include stem diameter, and the distance traveled between each contact of the vehicle and the trees. The work required to override single stems was determined by use of the following equation:

$$W_s = N\,(56\,d_s^{\,3})$$

where

W_s = total work (ft-lb) required to override the stems in a size class as if they were single standing stems overridden one at a time (see columns 5 and 6, table 4)

N = number of stems in a size class

d_s = stem diameter (in.), the midpoint of each size class was used.

The work required to override the same stems in a multiple array (W_o) was determined by use of the equation:

$$W_o = 1.07\,W_s^{\,1.088}$$

These values are listed in column 7 of table 4.

63. The distance traveled in overriding the stems in a specific sample is computed by converting the area of the sample cell (usually circular)

to a rectangular area whose width is equal to the width of the vehicle and long enough to cover an area equal to that of the sample cell. The length of the rectangle is considered to be the distance traveled by the vehicle when sweeping an area equal to that of the sample cell. The conversion equation is:

$$D_x = \frac{\pi D_c^2}{4\,W}$$

where

D_x = distance traveled, ft

D_c = diameter of the sample cell, ft

W = vehicle width, ft

The average force required to override stems in a multiple array (F_o) is determined by dividing the total work required to override the stems in the sample cell (W_o) by the distance traveled (D_x), as follows:

$$F_o = \frac{W_o}{D_x}$$

The relation between average force requ'red to override the stems and maximum diameter of stems to be overridden was computed for the GOER when operating in test course No. 5 (see table 4). This relation is shown i: fig. 21.

64. The trees at test course No. 5 were small (less than 6 in. diameter) and closely spaced; therefore the performance of the GOER was predicted on the basis of force requirements only with no consideration given to maneuver requirements. The following procedures were used to predict the speed of the GOER when controlled by the terrain force requirements of test course No. 5.

a. The motion resistance of the vehicle was assumed to be 3500 lb (see paragraph 51).

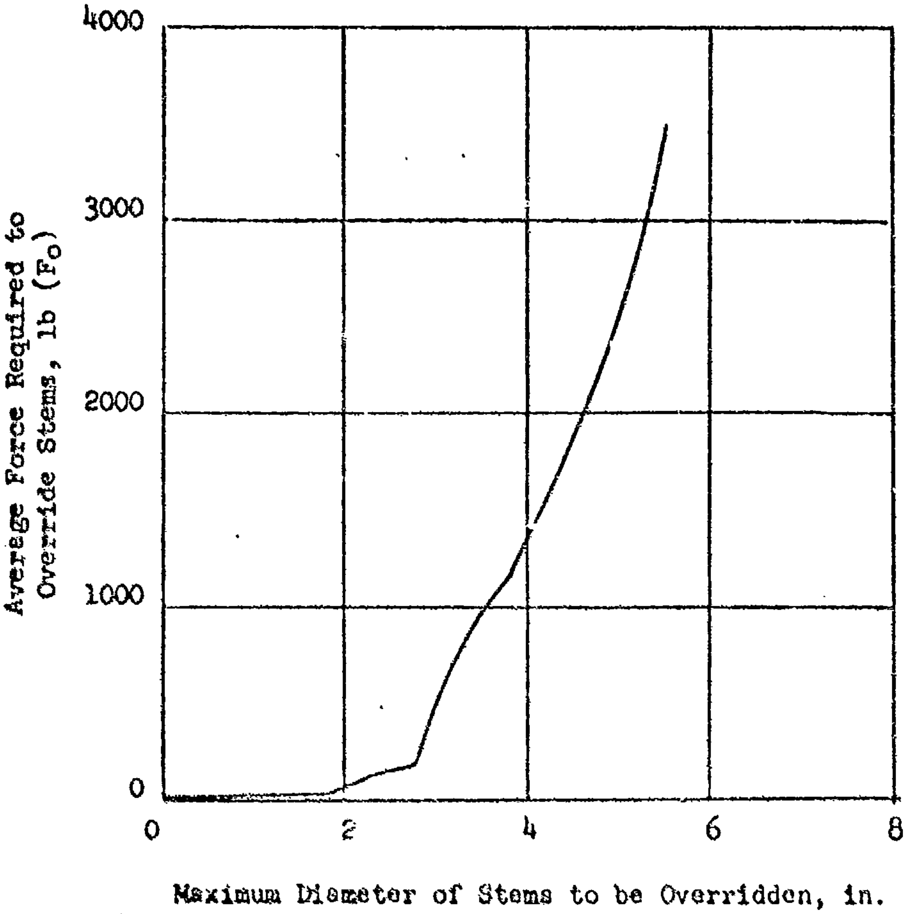


Fig. 21. Average force required-maximum stem diameter relation for the COER and test course No. 5.

b. The maximum average force required to override all the trees, no maneuvering, was computed to be 3491 lb (see column 7, table 4).

c. Now the total terrain force requirement is (3500 + 3491 = 6991) 6991 lb.

d. By referring to fig. 18b, it was determined that the GOER could maintain a speed of 6.3 mph and overcome the 6991 - lb terrain force requirement.

Evaluation of Predictions

65. The evaluation of the model predictions consisted of a direct comparison of predicted performance in terms of speed with actual test speeds. The actual average test speeds, the predicted average speed for the test course, and pertinent remarks are tabulated below.

Test Course No.	Test No.	Actual Average Test Speed mph	Predicted Average Test Speed mph	Remarks
1	1	16.7	15.8	Downslope predicted speed was 30.74 mph. Upslope predicted speed was 12.3 mph. The downslope distance was 984 ft and the upslope distance was 1672 ft
	2	10.8	12.3	Only upslope part of test course was used in this test
2	4 5	6.0 4.0	6.5 6.5	Speed predicted downslope was controlled by response to surface irregularities (10.2 mph). Speed predicted upslope was controlled by force demands (4.8 mph)

(Continued)

Test Course No.	Test No.	Actual Average Test Speed mph	Predicted Average Test Speed mph	Remarks
3	6	—	—	Test void, mechanical failure
4	7	0.0	0.0	"No go" was predicted for tests 7 and 8 because cone index of the muskeg was less than one-pass vehicle cone index of XM559 E1
4	8	0.0	0.0	
5	9	5.1	6.1	Speed (6.3 mph) was predicted by terrain force requirements, including 3491 lb of resistance by vegetation and 3500 lb by motion resistance
6	10	7.4	5.4	Predicted speed for tests 10 and 11 was controlled by vehicle's dynamic response to surface irregularities
	11	6.6	5.4	
7	12	4.5	4.2	Test was conducted upslope only; predicted speed was controlled by terrain force requirements
8	13	4.5	3.4	Test was conducted upslope only, but predicted speed was controlled by vehicle's dynamic response to surface irregularities
8	14	6.0	3.4	Test was conducted downslope only; predicted speed was controlled by vehicle's dynamic response to surface irregularities

A direct comparison of predicted and actual vehicle speeds is shown graphically in fig. 22. The average of the absolute deviation of actual from predicted speeds for the tests listed above is 1.36 mph. Notice that in test No. 5 the actual average speed was 2.5 mph slower than the predicted average speed. During test No. 4 the driver experienced discomfort due to ride dynamics; therefore, during test No. 5 the driver proceeded with extreme caution. It is believed that the difference in the actual average speeds of tests 4 and 5 was caused by driver influence. In test No. 14 the average actual speed was 2.6 mph faster than the predicted average speed. It is believed that the spacing of the surface irregularities in test course No. 8 caused the predicted effects of the irregularities to be more critical than the actual effects.

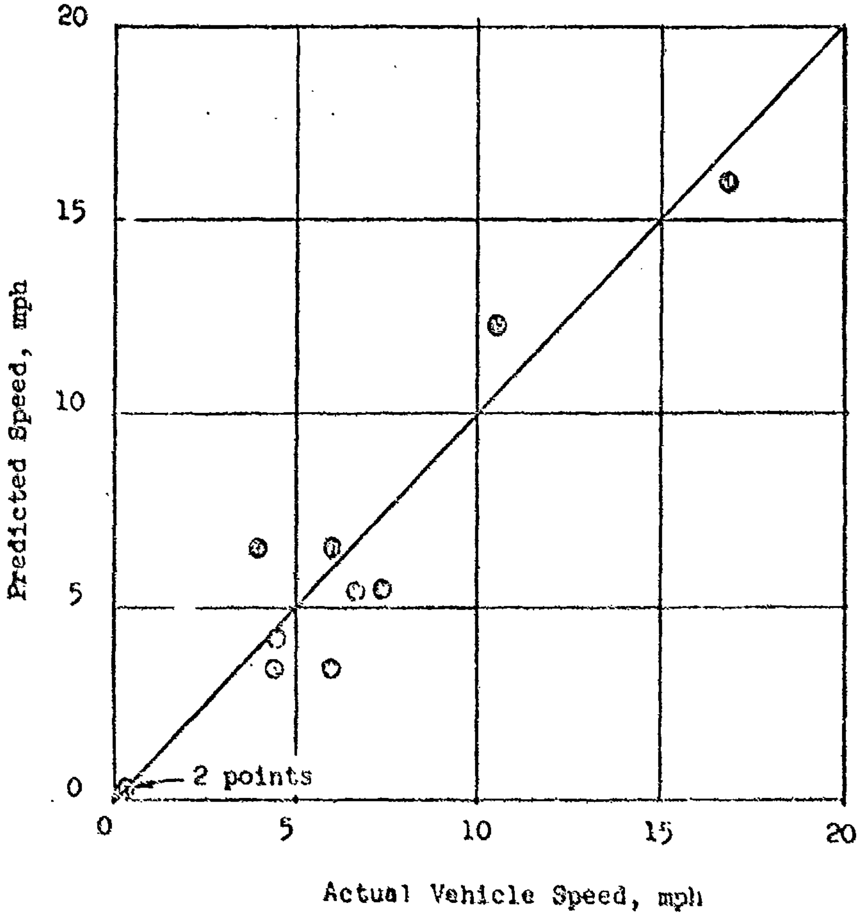


Fig. 22. Comparison of actual and predicted speeds

PART IV: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

66. Test results and observations made during the tests permit the following conclusions:

<u>a</u>. On a good secondary road with an average slope (up and down) of 6.64 percent, the fully loaded GOER maintained an average speed of 16.7 mph (see table, test No. 1).

<u>b</u>. In a cross-country situation where the soil was firm, there were no trees with diameters greater than 5.5 in., the most critical surface irregularities were less than 2 ft high and spaced about 100 ft apart, and where the maximum slope was 18.4 percent, the GOER's maximum average speed was approximately 6 mph (see tablel, tests 4, 5, 9-14).

<u>c</u>. The GOER was not able to cross Radforth type EFI, muskeg 20-32 in. deep having an average cone index in the 6- to 12-in. layer of 38 (see table 1, test 7 and 8).

<u>d</u>. The Wes Analytical model was used to predict the speed of a single vehicle (the GOER) in a limited number of terrain situations, with the following results:

Terrain	No. of Tests	Average Error of Prediction, mph
Secondary roads	2	1.20
General maneuver	7	1.45
Forested	1	1.00
Muskeg	2	0.00*
All terrains	12	1.36

* Not used in determining error of predictions for all terrains.

Recommendations

67. Based on the performance of the XM559E1 GOER over the selected Canadian terrains, it is suggested that the following design changes would improve its cross-country mobility.

- a. A more powerful engine is needed to improve the speed of the vehicle when extra tractive force is required to overcome resistance to motion caused by slopes, soft soil, etc.
- b. A suspension system is needed to increase the speed the vehicle can maintain when traveling over surface irregularities.
- c. More wheels and larger, softer tires would significantly improve the performance of the GOER when traveling in areas where the surface is composed of soft materials.

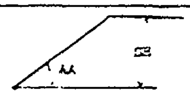
68. It is recommended that the effects of these design changes be evaluated by means of the WES analytical model to determine the feasibility of making actual changes in the design of the vehicle.

Table 1

Summary of Terrain Data, Actual Vehicle Speeds, and Predicted Vehicle Speeds

Test No.	Test Course No.	Surface Geometry Data: Avg Percent Slope	AA	SH	OS	Surface Composition Data: Cone Index 0–6 in.	6–12 in.	Vegetation Data: Spacing (ft) of Stems (in.) Greater Than: 1	2.5	4	5.5	7	8.5	Visibility: Recognition Distance (ft) at Height (ft) from Ground: 1.6	3.5	6.3	Terrain Class Designation	Actual Average Vehicle Speed Through Course mph	Predicted Average Vehicle Speed Through Course mph	Remarks
1	1	* 6.64	-	-	-	Firm	Firm	-	-	-	-	-	-	>500	-	-	SR	16.7	15.8	Downslope distance was 984 ft and upslope distance was 1672 ft. The up and downslope predicted speeds were 12.3 and 30.74 mph respectively.
2	1	** 8.22	-	-	-	Firm	Firm	-	-	-	-	-	-	>500	-	-	SR	10.8	12.3	Only the upslope part of the course was used in this test
++ 3	1	+ 5.24	-	-	-	Firm	Firm	-	-	-	-	-	-	>500	-	-	SR	-	-	Test conducted to determine motion resistance only. Motion resistance was 1057 lb
4	2	10.16	17	13	Random	120	205			Grass				>100	-	-	GM	6.0	6.5	Speed predicted downslope controlled by roughness (10.2 mph) Speed predicted upslope controlled by force demands (4.8 mph)
5	2	10.16	17	13	Random	120	205			Grass				>100	-	-	GM	4.0	6.5	
6	3	0.0	-	-	-	120	347	4.3	6.3	8.2	11.6	18.3		-	-	-	F	0.0	-	Test void, mechanical failure
7	4	0.0	-	-	-	21	38			95% grass cover				>100	-	-	X	0.0	0.0	Immobilization predicted by muskeg strength
8	4	0.0	-	-	-	21	38			95% grass cover				>100	-	-	X	0.0	0.0	Immobilization predicted by muskeg strength
9	5	2.0	30	17	Random	300+	300+	5.2	6.3	10.1	-	-	-	20	30	30	F	5.1	6.1	Speed predicted by surface roughness (6.1 mph)
10	6	2.0	30	9	Random	300+	300+			Short grass				>100	-	-	GM	7.4	5.4	Speed predicted by surface roughness (5.4 mph)
11	6	2.0	30	9	Random	300+	300+			Short grass				>100	-	-	GM	6.6	5.4	Speed predicted by surface roughness (5.4 mph)
12	7	16.2	—	—	-	300+	300+			Short grass				>100	-	-	GM	4.5	4.2	Speed predicted by force requirements, test conducted upslope only
13	8	18.4	45	11	Occasional	300+	300+			Short grass				>100	-	-	GM	4.5	3.4	Speed predicted by force requirements was 4 mph; test conducted upslope only
14	8	18.4	45	11	Occasional	300+	300+	Dense brush about 6 ft high						1	1	>100	GM	6.0	3.4	Speed predicted by surface roughness (3.4 mph); test conducted downslope

Surface geometry codes: AA - Obstacle approach angle, deg
SH - Obstacle step height, in.
OS - Obstacle spacing (usually in ft)



Terrain class designation codes: SR - Secondary roads
GM - General maneuver areas
F - Forested areas
X - Areas in which the surface foot or greater was composed of muskeg

NOTES:
* The average slope for the entire test course
** The average slope from Sta 7+85 to Sta 26+56
+ The average slope from Sta 23+56 to Sta 26+50
++ Test No. 3 was a free roll motion resistance

Table 2

Summary of Results of Drawbar Pull-Slip Tests

Reading No.	Drawbar Pull lb	Tractive Force* lb	Slip %
	Test DBP-1		
1	15,000	18,500	17.4
2	16,750	20,250	7.7
3	7,250	10,750	11.7
4	18,000	21,500	19.3
5	19,000	22,500	12.9
6	19,750	23,250	15.6
7	17,750	21,250	14.5
	Test DBP-2		
1	16,000	19,500	9.0
2	13,250	16,750	13.1
	Test DBP-3		
1	13,500	17,000	7.5
2	15,750	19,250	7.8
3	18,000	21,500	11.2
4	14,500	18,000	11.2
	Test DBP-4		
1	22,000	25,500	16.2
2	22,500	26,000	16.4
3	27,500	31,000	26.0
4	25,000	28,500	72.7
5	23,500	27,000	64.8
6	25,500	29,000	69.6
7	17,500	21,000	16.7

* Tractive force equals the average motion resistance measured in the area (3500 lb) plus drawbar pull.

Table 3

Mobility Index Versus Vehicle Cone Index

MI	VCI	MI	VCI	MI	VCI	MI	VCI	MI	VCI
0	3.0	31	39.2	67	55.6	103	72.0	139	88.3
0.25	5.5	32	39.7	68	56.1	104	72.4	140	88.8
0.50	7.0	33	40.1	69	56.5	105	72.9	141	89.2
0.75	8.3	34	40.6	70	57.0	106	73.3	142	89.7
1.00	9.0	35	41.0	71	57.4	107	73.8	143	90.1
1.50	10.8	36	41.5	72	57.9	108	74.2	144	90.6
2.00	12.5	37	42.0	73	58.3	109	74.7	145	[illegible].0
2.50	13.8	38	42.4	74	58.8	110	75.1	146	91.5
3	15.1	39	42.9	75	59.2	111	75.6	147	91.9
4	17.5	40*	43.4*	76	59.7	112	76.0	148	92.4
5	19.7	41	43.8	77	60.2	113	76.5	149	92.8
6	21.5	42	44.3	78	60.6	114	77.0	150	93.3
7	23.0	43	44.7	79	61.1	115	77.4	151	93.8
8	24.2	44	45.2	80	61.5	116	77.9	152	94.2
9	25.3	45	45.6	81	62.0	117	78.3	153	94.7
10	26.4	46	46.1	82	62.4	118	78.8	154	95.1
11	27.3	47	46.5	83	62.9	119	79.2	155	95.6
12	28.1	48	47.0	84	63.3	120	79.7	156	96.0
13	28.9	49	47.4	85	63.8	121	80.1	157	96.5
14	29.6	50	47.9	86	64.2	122	80.6	158	96.9
15	30.4	51	48.4	87	64.7	123	81.0	159	97.4
16	31.0	52	48.8	88	65.2	124	81.5	160	97.8
17	31.7	53	49.3	89	65.6	125	82.0	161	98.3
18	32.3	54	49.7	90	66.1	126	82.4	162	98.7
19	32.9	55	50.2	91	66.5	127	82.8	163	99.2
20	33.5	56	50.6	92	67.0	128	83.3	164	99.6
21	34.1	57	51.1	93	67.4	129	83.8	165	100.1
22	34.6	58	51.5	94	67.9	130	84.2	166	100.6
23	35.2	59	52.0	95	68.3	131	84.7	167	101.0
24	35.8	60	52.4	96	68.8	132	85.1	168	101.5
25	36.3	61	52.9	97	69.2	133	85.6	169	101.9
26	36.8	62	53.3	98	69.7	134	86.0	170	102.4
27	37.3	63	53.8	99	70.1	135	86.5	171	102.8
28	37.8	64	54.2	100	70.6	136	86.9	172	103.3
29	38.3	65	54.7	101	71.1	137	87.4	173	103.7
30	38.7	66	55.2	102	71.5	138	87.8	174	104.2

For MI's above approximately 40, VCI obtained from equation
$VCI = 25.2 + 0.454 \times MI$.

Table 4

A Summary of Vegetation Data, Stem Spacing, and Force Computations for the GOER and Test Course No. 5

(1) Stem Diameter Class in.	(2) No. of Stems in Each Class	(3) No. of Stems in the Cell Greater than the Upper Limit of Each Class	(4) Mean Spacing (ft) of those Stems Greater than the Upper Limit of Each Class	(5) W_s	(6) ΣW_s	(7) ΣW_o	(8) F_o
0.5-1.0	0	56	5.2	0	0	0	0
1.1-1.5	6	50	5.5	655	655	1160	9
1.6-2.0	5	45	5.8	1501	2156	4537	35
2.1-2.5	7	38	6.3	4465	6621	15365	120
2.6-3.0	3	35	6.6	3493	10114	25380	198
3.1-3.5	16	19	8.9	30751	40865	101280	791
3.6-4.0	4	15	10.1	11812	52677	146590	1145
4.1-4.5	5	10	12.3	21493	74170	212502	1660
4.6-5.0	4	6	15.9	24004	98174	288686	2255
5.1-5.5	6	0	--	48616	146790	447046	3491
5.6-6.0	0	0	--	--	--	--	--

Notes:

1. The diameter of the sample cell was 39 ft.
2. W_s is work (ft-lb) required to override the trees in each class, one at a time.
3. ΣW_s is total work (ft-lb) required to override the stems equal to or smaller than those in each class, singularly.
4. ΣW_o is total work (ft-lb) required to override the stems equal to or smaller than those in each class, in a multiple array.
5. F_o is the average force (lb) required for the GOER to override the stems equal to or smaller than those in each class, in a multiple array.